Experiences with three tillage systems on a marine loam soil
II: 1976 – 1979

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A joint study of the Westmaas Research Group on New Tillage Systems, carried out on the Westmaas Experimental Husbandry Farm

Pudoc Wageningen 1984

CIP-GEGEVENS

Experiences

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Abstract

Westmaas Research Group on New Tillage Systems, 1984. Experiences with three tillage systems on a marine loam soil II: 1976 - 1979. Agric. Res. Rep. (Versl. landbouwk. Onderz.) 925, ISBN 90 220 0855 X, (xi) + 263 p., 126 tables, 102 figs, 68 refs, English summary.

During 1976 - 1979 the concluding part of a field experiment was conducted which had been started in the autumn of 1971 on a marine loam soil (22% clay) at Westmaas Experimental Husbandry Farm. Three tillage systems were compared in a four-year crop rotation: potatoes - winter wheat + undersown grass - sugar beet - spring barley + undersown grass. In loose-soil husbandry (System A), primary tillage was 25 cm ploughing for all crops and secondary tillage and sowing or planting were combined into one pass to reduce traffic intensity and therefore compaction. In no-tillage (System B), primary tillage was omitted and either only a seedbed was prepared (System B1) or, in an alternative crop rotation with seed grass - winter wheat + undersown grass - field beans - spring barley + undersown grass, direct drilling was performed (System B2). In rational tillage (System C), primary tillage was ploughing tot 25 cm depth (for sugar beet) or to 15 cm depth (for potatoes), or fixed-tine cultivation to 15 cm depth (for cereals). In late winter, the effect of tillage-induced changes in soil mineral nitrogen content was assessed by sampling the soil profile to 1 m depth. Crop response to fertilizer nitrogen was studied by means of five annual nitrogen levels and three perennial nitrogen levels, ranging from 0 to 200% and from 80 to 120%, respectively, of the amounts normally applied in the region.

In comparable tilled layers, System A did not give a looser soil structure than System C, mainly because soil compaction by field traffic was only sligthly reduced; usually crop yields were similar. Systems B1 and B2 produced a very compact soil with a high mechanical resistance, a sometimes insufficient aeration and an initially slower root and shoot development; to achieve about the same cereal yields as obtained in Systems A and C, nitrogen rates had to be inreased by 15 - 20%. In System B1, seedbed preparation in spring usually was difficult since untilled soil remains wet much longer than tilled soil; sugar yield of sugar beet and saleable yield of potatoes were about 10% less than in Systems A and C. In System B2 the uneven surface (wheel tracks and dips) was sometimes ponded, which induced suffocation of seedlings. Sometimes the seed was insufficiently covered, which resulted in severe damage by birds. Soil structure regeneration occurred only in the surface layer and cereal yields were slightly lower than in System B1; yields of field beans and seed grass yields were satisfactory. Initially, in untilled soil, nitrogen availability in January was less but after four years in System B1 it was equal to that in tilled soil. In System B2 this situation was reached at least two years later. In both Systems B1 and B2 more annual and perennial weeds developed, which required additional herbicide applications and hand-weedings. Under Dutch conditions, even in a rotation without root crops, 'pure' no-tillage (System B2) is financially not attractive.

Free descriptors: Loose-soil husbandry, no-tillage, reduced tillage, direct drilling, rational tillage, crop rotation, soil structure, soil aeration, mechanical resistance, penetration resistance, remote sensing, nitrogen availability, root growth, weed control, potatoes, winter wheat, sugar beet, spring barley, economical evaluation, after-effects.

Contents

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Foreword

A. van der Schaaf

Narrow crop rotations with forty or more percent of root crops, such as potatoes, sugar beet, onions and flower bulbs, are common on Dutch arable farms. As a consequence, the soil is used very intensively. These cropping systems, which include intensive field traffic and harvest operations make great demands of the soil structure. The deterioration of soil structure caused by traffic during the growing season, harvest operations and transport of products, and sometimes even soil fumigation, have to be alleviated by appropriate primary tillage operations.

To extend the growing season, the harvest of ware potatoes and sugar beet is often delayed. Primary tillage is then postponed and frequently carried out under unfavourable soil conditions. Moreover, these crop rotations hardly allow the growing of green manure crops. It is evident that in these circumstances, soil structure is under almost permanent stress. Research and practice have proved that under conditions of optimal soil management, including the appropriate use of modern tillage implements, the structure of the arable layer can be improved quite rapidly. Nevertheless, the cumulative stress of successive years may be dangerous for the physical properties of the arable layer. In this context, not much is known of the subsoil. However, it is known that surface compaction and subsoil compaction may have additive effects on crop yields. Compaction in deeper layers persists for a long time and it is evident that alleviation of this is more difficult and expensive than that of the arable layer. However, how strongly crops may respond to soil compaction is insufficiently known.

The increasingly heavy machinery used in rotations with mainly root crops will influence the topsoil, and perhaps even the subsoil. For this reason research on tillage systems based on a range of soil densities is needed. But there are more questions. When the soil is tilled in a traditional way, weed control with chemicals normally meets its objectives. But what are the consequences for weed prevention and weed control in different tillage systems? Lengthening of the growing season frequently enables greater crop production. Is it possible to lengthen the growth period both in autumn and in spring by adapting the commonly used tillage systems? Energy costs are increasing rapidly. Is it possible to reduce energy requirements and still to increase farm productivity by using a lower intensity of tillage?

To answer such questions, a soil tillage experiment, including a four-year crop rotation and three tillage systems, was started in the autumn of 1971 (Westmaas Research Group on New Tillage Systems, 1980). The present report deals with the second crop rotation (1976 - 1979) and gives the final conclusions from the whole experiment. The original cooperation between research workers of the Tillage Laboratory of the Agricultural University, the Institute for Soil Fertility (IB), the Centre for Agrobiological Research (CABO), the Research Station for Arable Farming and Field

Production of Vegetables (PAGV) and the Westmaas Experimental Husbandry Farm (EHF) was extended during the second rotation. Attention to additional aspects, such as root development in relation to the soil profile, the use of tractive power and energy, and, last but not least, the economic aspects and consequences of the tillage systems was given by cooperation with the Soil Survey Institute (Stiboka), the Institute of Agricultural Engineering (IMAG) and the Economics Department of PAGV.

This extension of the research activities was possible thanks to the efforts of Professor Ir H. Kuipers and Ir G. J. Poesse, president and secretary, respectively, of the Coordinating Committee on Soil Tillage of the National Board for Agricultural Research, to have the experiment centrally funded by the Ministry of Agriculture and Fisheries. In this way, the organisation of the research collaboration became more efficient. The executive committee took care of all field operations and the research committee coordinated the research and reporting activities. Convinced of the importance of this kind of research for farm practice, the late Ir K.B. van Gilst inspired the whole team of researchers and the members of the executive committee, of which he was president. The experiment was managed by Ing J. Alblas and Mr C. Vader whose reporting was valuable. The executive committee closely cooperated with the farm manager, Mr H.J. Kram.

Thanks are due to the Board of the Westmaas Experimental Husbandry Farm, which, convinced that the often very theoretical-looking project would in the long run serve practical purposes, made the project possible by offering an experimental field for a very long period. Although every participant in the project collaborated in the writing of this research report, it was Ir F.R. Boone (Tillage Laboratory) who took on the difficult task of editing, for which we are very grateful. Thanks are also due to Ir C. van Ouwerkerk (Institute for Soil Fertility) for his linguistic recommendations. We hope that both research and farm practice will take advantage of the results of this soil tillage experiment.

Acknowledgments

The authors are indebted to Messrs C. Vader and H. Kram (Westmaas EHF) and to Mr J. Alblas (Research Station for Arable Farming and Field Production of Vegetables) for their careful management of the field operations and for their reporting of all noteworthy facts concerning the soil and the crops on the experimental field.

Field and laboratory determinations were performed by Messrs B. Kroesbergen and A. Boers (Tillage Laboratory, Agricultural University), I. Ovaa (Soil Survey Institute) and M. Pot (Institute for Soil Fertility). Messrs L. ten Holte (Centre for Agrobiological Research) and J. Klooster (Institute of Agricultural Engineering) assisted in special field operations.

Messrs M. Pot (Institute for Soil Fertility), B. Kroesbergen (Tillage Laboratory, Agricultural University) and H.C. Bos (Soil Survey Institute) deserve a special word of thanks for the drawings they prepared.

1 Layout of the experiment

L.M. Lumkes

1.1 Location and soil characteristics

The research, which was started in autumn 1971 (Westmaas Research Group on New Tillage Systems, 1980) and continued until 1980, was carried out on the Westmaas Regional Experimental Husbandry Farm (EHF) in the Hoeksewaard polder, which is situated in the marine clay district in the southwest of the Netherlands (Fig. 1).

The calcareous alluvial soil of this farm belongs to the very important group of polder vague soils (de Bakker, 1979) with loam in the plough layer and clay content decreasing with depth. Table 1 provides some analytical data of the soil profile. The chemical composition of the fertile arable layer is 19 mg K per 100 g, 65 mg Mg per kg, 10 mg P per 100 g (P_w 23) and 0.14 g N-total per 100 g.

Many arable soils in the southwest of the Netherlands have a distinct compacted layer just below the tilled soil (Stiboka, 1971). This layer, generally described as ploughpan, cannot be restored by normal tillage, only by deep tillage. However, because of the risks of re-compaction after loosening, a ploughpan is often accepted. On the experimental field, a rather severe ploughpan was found at a depth of 30 - 35 cm.

The experimental field was intensively drained. Tile drains were installed at a depth of 1.1 m with a horizontal spacing of between 7.2 and 9.2 m. The direction of the drains was roughly perpendicular to the direction of the tillage operations. The depth of the groundwater table fluctuated between 0.5 to 1.0 m in winter and 1.5 to 2.0 m in summer.

1.2 Tillage systems

The main soil tillage operation is carried out to improve soil structure of the arable

Table 1. Characteristics of the soil profile (0-100 cm).

Horizon	Depth (cm)	Org. matter (%, w/w)	Particle-size distribution of mineral fraction (%, w/w of fine earth)					$CaCO_3$ (%, w/w)	pH (KCl)
			<2	2 - 16	16 - 50	50 - 105	>105 μm		
Ap1, Ap2	0 - 31	2.3	22	11	33	32	2	8.3	7.3
C21g	31 - 37	1.2	17	9	37	34	3	12.8	7.5
C22g	37 - 50	1.2	15	9	40	34	3	13.4	7.6
C23g, C24g	50 - 100	1.2	11	7	33	45	5	12.1	7.8

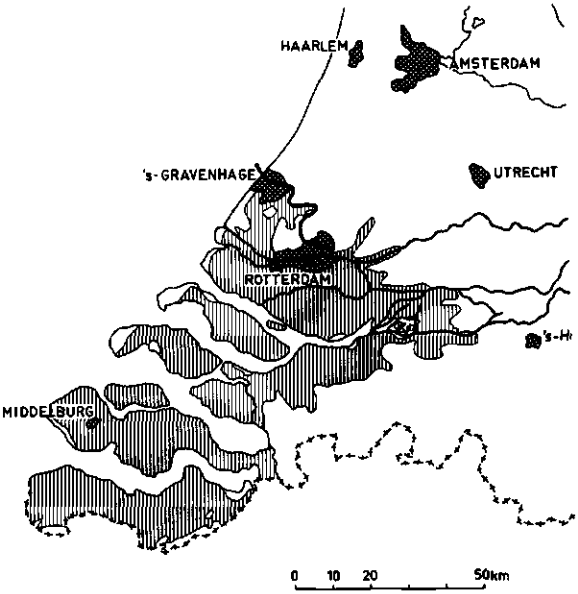

Fig. 1. The marine clay district in the southwest of the Netherlands.

layer and to incorporate residues of the previous main crop and – if present – the green manure crop. It is also a first step in preparing an optimal seedbed for the next crop and the control of weeds. In traditional arable farming, the loosening effect of this soil tillage operation, however, is lost in subsequent field operations. In narrow crop rotations with a high percentage of root crops, associated with increasingly heavy transport of products (>50 t ha^{-1}), soil structure may be damaged to such an extent that subsequent tillage operations cannot fully restore the optimal situation.

To study the counteracting loosening and compacting effects and their influence on crop growth, three distinct tillage systems were compared in triplicate on plots of 30 m x 50 m. The layout of the experiment is given in Fig. 2. The systems studied are summarized in Table 2. They can be characterized as described below.

System A – Loose-soil husbandry This system aims at producing and maintaining a loose soil by ploughing every year to the full depth of the arable layer (25 cm) and by minimizing the number of passes by combining field operations.

System B – No-tillage This system is the opposite of System A because during the whole experiment the main tillage operation was omitted. In principle, soil tillage was restricted to seedbed preparation and ridging for potatoes, and harvesting of root crops. In System B1, with a crop rotation including root crops, during the first four-year crop rotation (1972 – 1975) no seedbed was prepared, except for potatoes. During the second crop rotation (1976 – 1979), however, a (shallow) seedbed was made for all crops. In System B2, a crop rotation with non-root crops only, all crops were always sown without seedbed preparation.

Table 2. Tillage systems compared during 1976 - 1979 in the main crop rotation (with root crops).

Crop	Loose-soil husbandry (A)	No tillage (B1)	Rational tillage (C)
Potatoes	plough 25 cm seedbed prep.[a] + planting + ridging (1 pass)	– rotavator 7 cm, planting (2 passes) row-rotavating + ridging (1 pass)	plough 15 cm seedbed prep., planting (2 passes) row-rotavating + ridging (1 pass)
Winter wheat	cultivator 5 cm[b] plough 25 cm + sowing (1 pass); no seedbed prep.	cultivator 5 cm[b] cultivator 6 cm + sowing (1 pass); no seedbed prep.	cultivator 5 cm[b] cultivator 15 cm + sowing (1 pass); no seedbed prep.
Sugar beet	plough 25 cm seedbed prep.[a] + sowing (1 pass)	rotavator 3 cm, sowing (2 passes)	plough 25 cm seedbed prep., sowing (2 passes)
Spring barley	cultivator 5 cm[b] plough 25 cm seedbed prep. + sowing (1 pass)	cultivator 5 cm[b] seedbed prep. + sowing (1 pass)	cultivator 5 cm[b] cultivator 15 cm[c] seedbed prep. + sowing (1 pass)

a. In 1978 combined with N fertilization.
b. Levelling with spring-tine cultivator (across the field).
c. In 1975 length-wise; in 1976 - 1978 across the field.

System C – Rational tillage This system represents current progressive farming methods (van Ouwerkerk, 1974). Ploughing for root crops alternates with fixed-tine cultivation for cereals. For cereals, the fixed-tine cultivator is a good alternative for ploughing (van Ouwerkerk, 1976). Moreover, after fixed-tine cultivation, the chance that potatoes lost at harvest are killed by frost is substantially increased (Lumkes & Beukema, 1973; Lumkes, 1974).

1.2.1 Differences in the content of the tillage systems between the first and the second crop rotation

The first crop rotation (1972 – 1975) represents a period of the experiment in which differences in soil structure between tillage systems were progressively built up. However, differences in soil structure between Systems A and C were smaller than hoped for. Therefore, with improved handling of equipment, during the second crop rotation it was tried to optimize the systems and to increase the differences in soil structure. Compared with the first crop rotation the following small changes were introduced:

– Because all other field work was done length-wise, and more or less in the same wheel tracks, it was increasingly necessary to level the surface. This was done in Systems A, B1 and C, following the potato and sugar beet harvest, by working shallowly across the field with a spring-tine cultivator.

– In System A, the ploughing depth for cereals was increased from 20 to 25 cm. However in System C, the ploughing depth for potatoes and the depth of fixed-tine cultivation for cereals were reduced from 20 to 15 cm. As a result, System C differed more from general

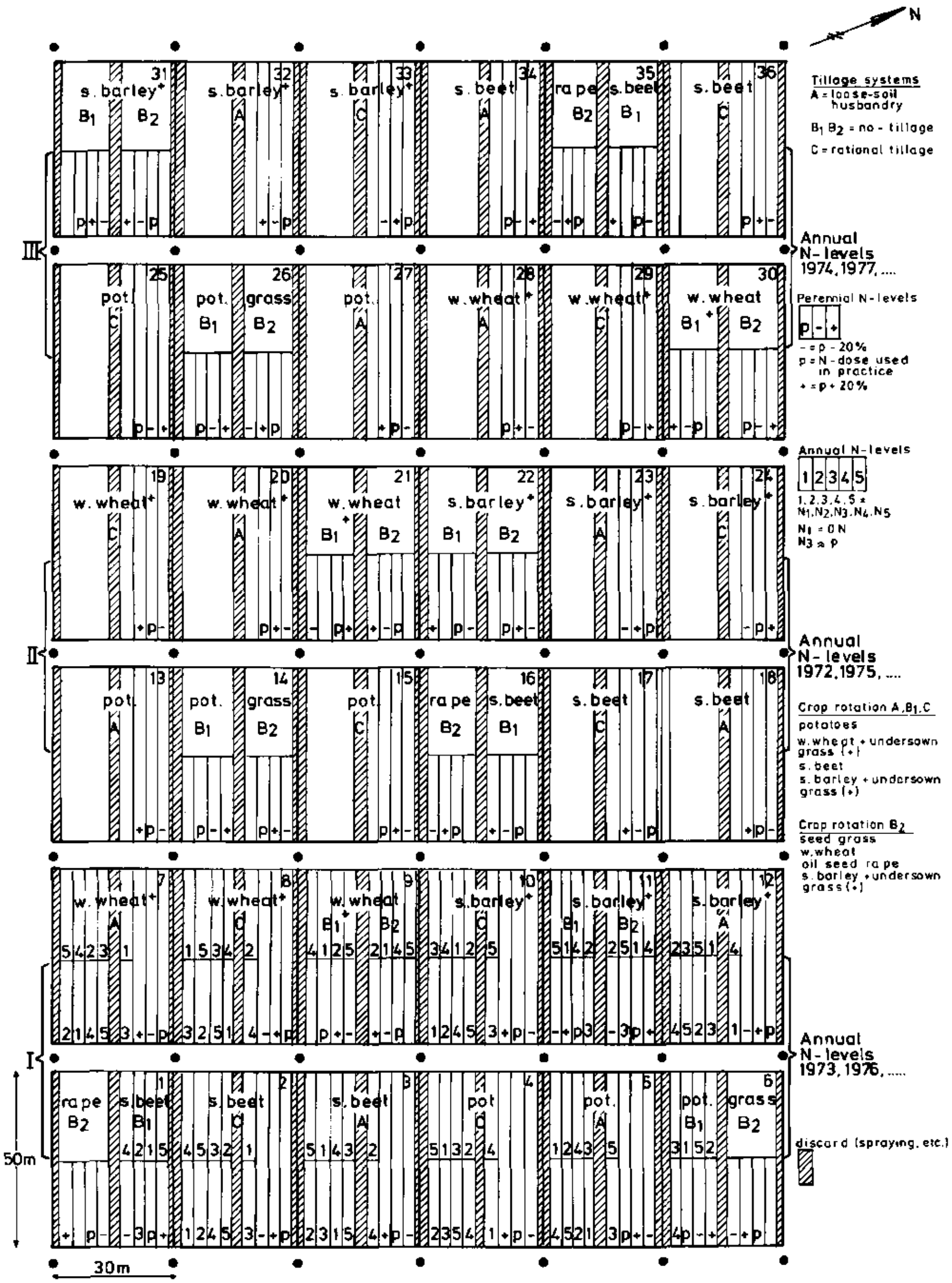

Fig. 2. Layout of the experiment.

practice than during the first crop rotation; in this region of the Netherlands farmers prefer to till the soil to at least 20 cm depth.
– In System C, when performing fixed-tine cultivation after sugar beet (late in the season), the previously levelled, loose soil was often wet, which induced extreme wheelslip. Therefore, in autumn 1975, to pull the fixed-tine cultivator length-wise, two tractors (Ford 5000 + MF 35) were needed. In 1976 – 1978 wheelslip could be overcome by working the fixed-tine cultivator across the field, i.e. more or less in the path of the spring-tine cultivator teeth.

Because in System B1 during the first crop rotation, emergence appeared to be unsatisfactory on many occasions, during the second crop rotation, a (shallow) seedbed was prepared for all crops. Thus the 'pure' no-tillage concept was more or less abandoned and changed into an extreme reduced-tillage system, still without any main tillage. However, all crops could now be sown with the same equipment used in Systems A and C.

During the first rotation it was observed that an uneven distribution of high amounts of winter wheat straw disturbed the emergence of sugar beet in System B1. Therefore, in System B1, except for 1978, the winter wheat straw was baled and removed. For the same reason, in 1976 and 1977 also in System B2 the winter wheat straw was removed. In Systems A and C straw incorporation was continued.

1.3 Crop rotation

The main crop rotation in the experiment was potatoes – winter wheat (with undersown grass) – sugar beet – spring barley (with undersown grass), which is representative for the marine clay district of the southwest of the Netherlands. The grass green manure, as well as the tops and leaves of sugar beet and chopped straw, were incorporated into the soil (Systems A and C) or, after treatment with herbicides, left on the surface as mulch (System B). However, as mentioned above, in System B the winter wheat straw was usally removed.

In principle, the no-tillage system is not suitable for potatoes and sugar beet, as seedbed preparation and harvesting operations for these root crops necessitate a fair amount of tillage. The inherent soil disturbance may have a negative effect on the soil as it prevents the soil fauna from creating a stable soil structure, a characteristic of the 'pure' no-tillage system. To be able to study this effect the plots marked out for the no-tillage system were split in two halves, one with the main crop rotation as described above (B1), and one with a crop rotation with non-root crops only (B2): seed grass – winter wheat (with undersown grass) – field beans – spring barley (with undersown grass).

1.4 Fertilization

1.4.1 Nitrogen

Crop response to tillage-induced changes in the nitrogen status of the soil was established for two different nitrogen regimes:

a. Annual nitrogen levels Equidistant application of five amounts of nitrogen, ranging

Table 3. Annual nitrogen levels (kg ha^{-1}), 1976 - 1979.

Crop	N1	N2	N3	N4	N5	(N6[a])
Potatoes	0	80	160	240	320	
Winter wheat	0	40	80	120	160	
Sugar beet	0	60	120	180	240	(300[a])
Spring barley	0	20	40	60	80	

a. Supplementary in 1979.

from 0 to 'X' kg ha^{-1} N on plots with the main crops potatoes, sugar beet, winter wheat and spring barley (Table 3), in duplicate in Systems A and C and usually without replication in Systems B1 and B2. Each year the nitrogen levels were applied to one replicate, and they were circulated over the three replications to prevent residual effects (Fig. 2).

b. Perennial nitrogen levels To induce cumulative effects, this fertilization regime was reproduced each year on all main-crop plots of all three replications of the experimental field. The basic application (P) was more or less the optimum amount of nitrogen applied by farmers in practice. A 20% smaller dose (P –) and a 20% larger dose (P +) were applied to establish to what extent crop response to tillage-induced changes in soil structure can be influenced by a consistent nitrogen fertilization regime. Periodical analysis of the soil nitrogen status in late winter was used to adapt the perennial nitrogen levels. In some crops and replicates, and in different years, the level and the differences in nitrogen dressings were therefore not always the same (Table 4). At low levels, as for barley, the relative differences were larger (up to 200%).

1.4.2 Phosphate and potassium

In all tillage systems the same amounts of phosphate and potassium were applied (Table 5). Winter wheat and spring barley were not fertilized with phosphate and potassium because in the Netherlands it is known by experience that in a crop rotation with 50% cereals a sufficient amount of these elements remains in the soil after the

Table 4. Basic application (P) of nitrogen on plots with perennial nitrogen levels (kg ha^{-1}), 1976 - 1979[a].

Crop	Year			
	1976	1977	1978	1979
Potatoes	240	230	240	280
Winter wheat	80	20 - 40	80 - 100 (140)	100 - 140
Sugar beet	160	140	80 - 160	180
Spring barley	40	20	20 - 60	40 - 100

a. A range indicates that nitrogen dressings were different for different replications.

Table 5. Phosphate and potassium fertilization (kg ha [1]), 1976 1979.

Potatoes	P_2O_5	K_2O
Potatoes	200	500
Winter wheat	-	
Sugar beet	150	150
Spring barley	-	
Seed grass	100	150
Field beans	100	150

previous root crops. In all systems, phosphate and potassium were applied in autumn between cereal harvest and the main soil tillage operation, as this causes least damage to soil structure.

1.5 Experimental design

Each year all crops of both rotations (with and without root crops) were present on all three replications of the experiment (Fig. 2). In each replicate there were crop blocks in which the tillage systems had a fixed position. The gross size of the experimental field was 6.3 ha (180 m×350 m). The plots of Systems A and C had a size of 30 m×50 m = 1500 m^2, whereas those of Systems B1 and B2 were 15 m×50 m = 750 m^2. In all plots nitrogen sub-plots were arranged in strips with a width of 3 m, corresponding to the working-width of the fertilizer drill used. The direction of all field traffic was in the length of the plots, which resulted in a more or less fixed wheel track pattern. In Systems A, B1 and C, following root crops, shallow spring-tine cultivation across the plots was practiced to level the soil surface. The layout of the experiment is explained in more detail in the report of the first rotation (Westmaas Research Group on New Tillage Systems, 1980).

1.6 Machinery used

Generally, the same machinery was used and the same methods were applied during the second crop rotation as in the first crop rotation 1972 - 1975 (Westmaas Research Group on New Tillage Systems, 1980). Changes in the content of the tillage systems introduced after the first crop rotation were already discussed in Section 1.2.1. The essentials of the content of the tillage systems compared during the period 1976 - 1979, are summarized in Table 2.

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2 Traffic intensity

L.M. Lumkes

2.1 Introduction

In this chapter a description of the tractors, machinery and equipment used and the traffic pattern on the experimental plots is given. It includes information on the intensity of field traffic and the load on the soil in footprints marked for each pass. The tractor and machinery operations are based on two factors:

a. the three tillage systems, differing in level and method of mechanization to realise the intended variation in soil structure (Table 2);

b. the layout of the experiment with plots of 30 m wide and 50 m long, which were split into 3 m wide nitrogen sub-plots (Fig. 2).

If possible, in System A field operations were combined: seedbed preparation, planting and ridging of potatoes, seedbed preparation and drilling of sugar beet and spring barley, and primary tillage (ploughing) and drilling of winter wheat. In Systems B1 and C, seedbed preparation and drilling of cereals were also combined. For these combined operations, a bridge-link (sulky) had to be used for planting potatoes and drilling sugar beet in System A and for drilling winter wheat in Systems B1 and C. All spraying of herbicides, fungicides and pesticides was done from gross strips between main plots and is, therefore, not included in the traffic pattern.

2.2 Methods

Based on the dimensions of the machinery used (as supplied by the manufacturer), supplemented by own measurements, the footprints of the wheels of tractor(s) and implements in the field are given for each seperate pass (Figs. 3 – 7) for the four main crops in Systems A, B1 and C. The footprint means the contact area of the tyre with the soil. When driving over the field the contact area and the soil pressure may be higher, however. When the position of the footprints was known exactly the footprints in the sketches were hatched. If not, which was the case for ploughing and most traffic at root crops harvest, the footprint-block is white. In the figures the forward direction is indicated by means of an arrow, the second pass by the digit 2, while the letters L or R mean the left or the right wheel, respectivily. All tractors used had a track gauge of 1.50 m for the standard front and rear wheels. Twin wheels were used only at seedbed preparation and at planting or drilling; narrow wheels were used for interrow cultivation. Generally, the depth of compaction by wheels is up to 0.5 – 0.7 times the width of the tyre (Table 6); compaction is strongest under the centre of the tyre (Söhne, 1953; Söhne & Bolling, 1982).

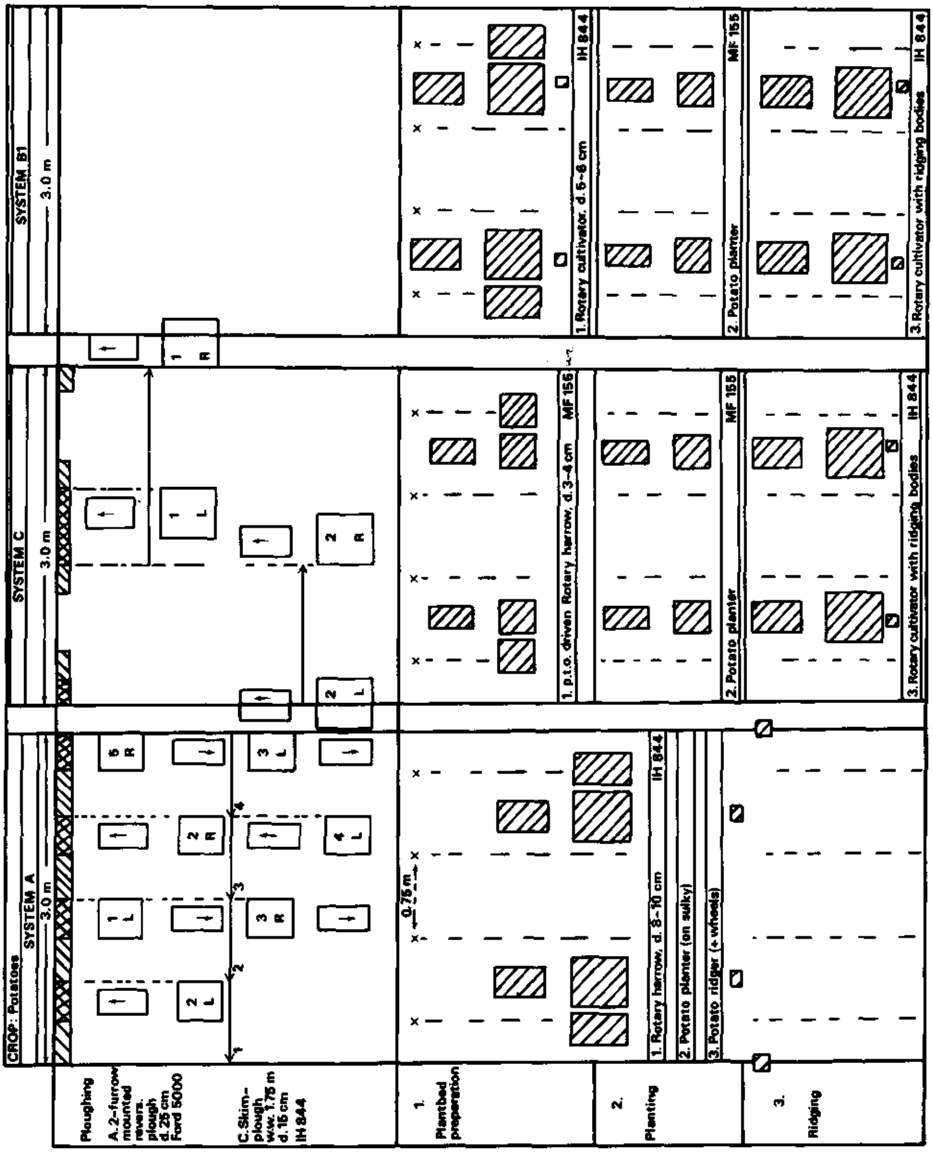

Fig. 3. Driving pattern for potatoes.

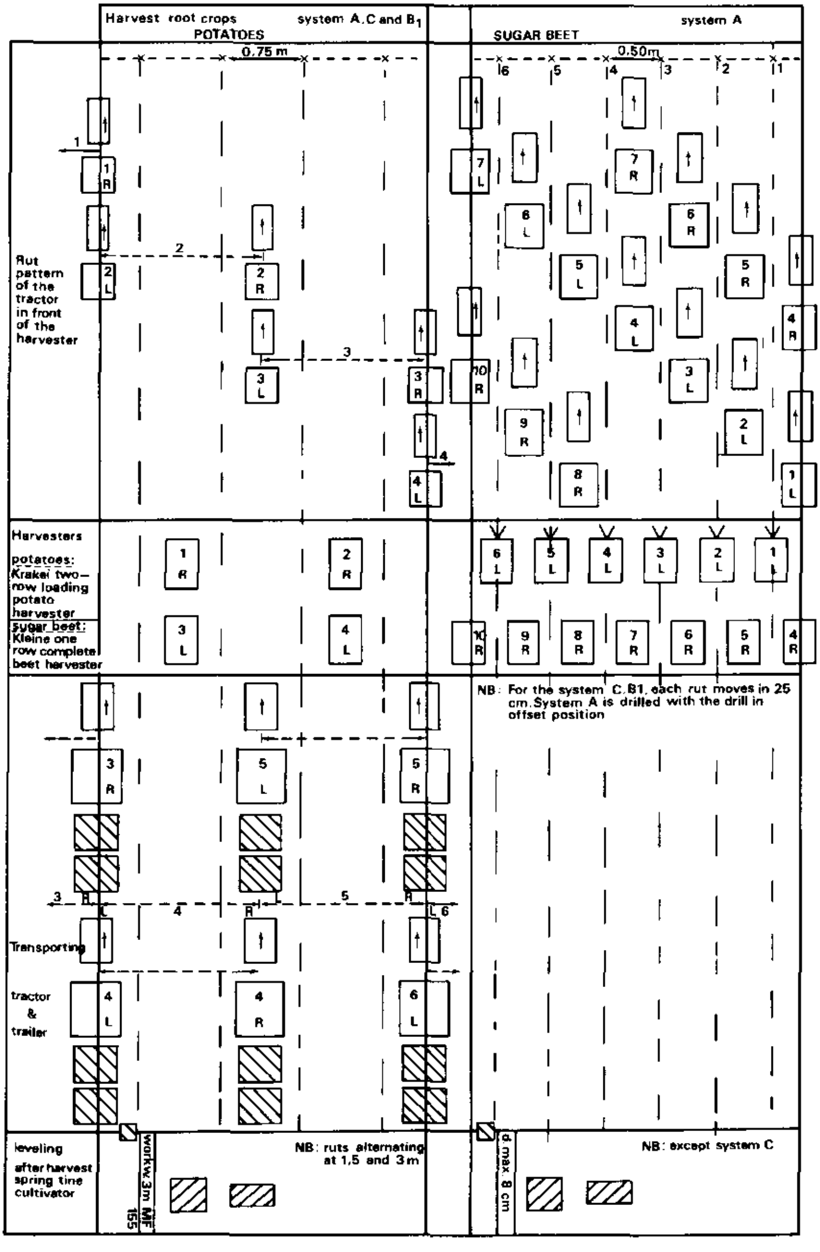

Fig. 4. Traffic pattern for root crops harvest and soil levelling afterwards (cross-wise).

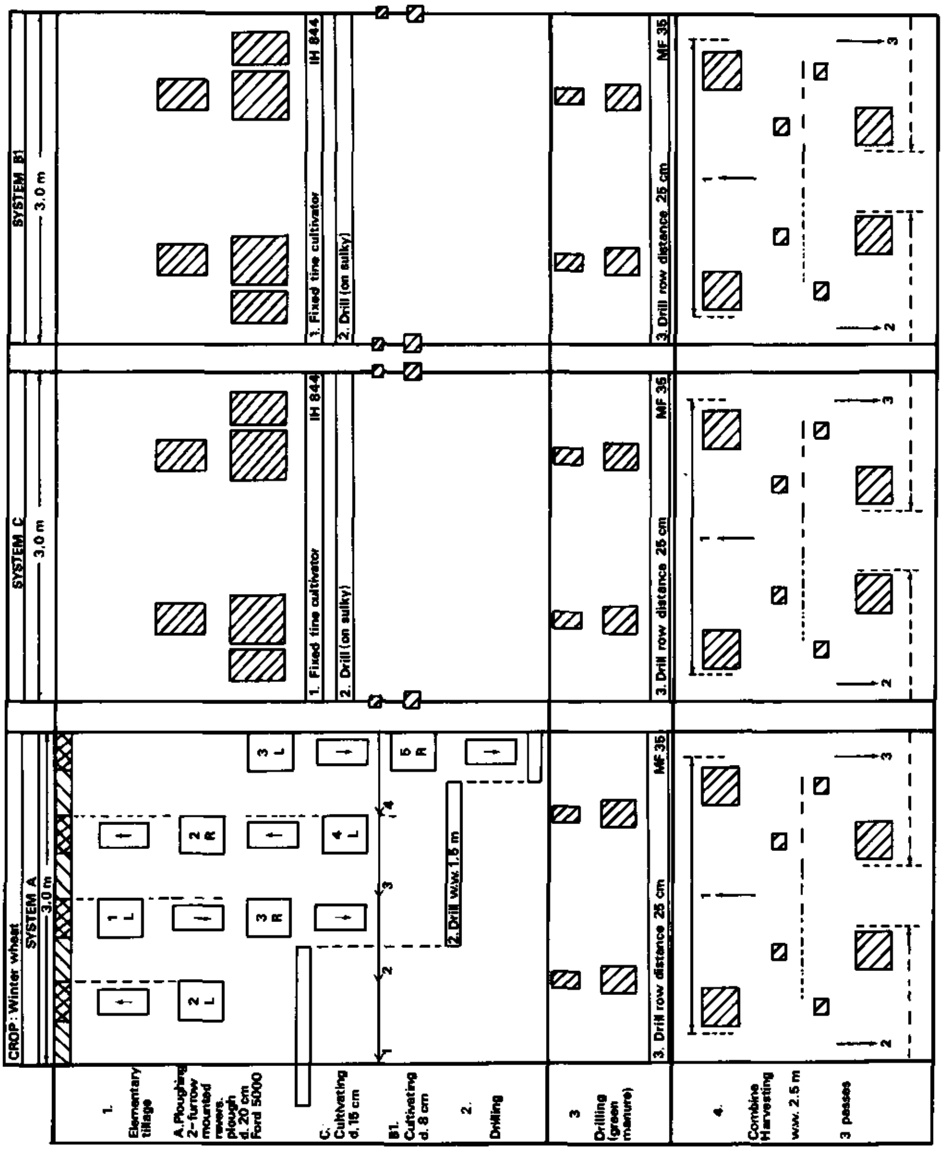

Fig. 5 Driving pattern for winter wheat.

Fig. 6 Driving pattern for sugar beet.

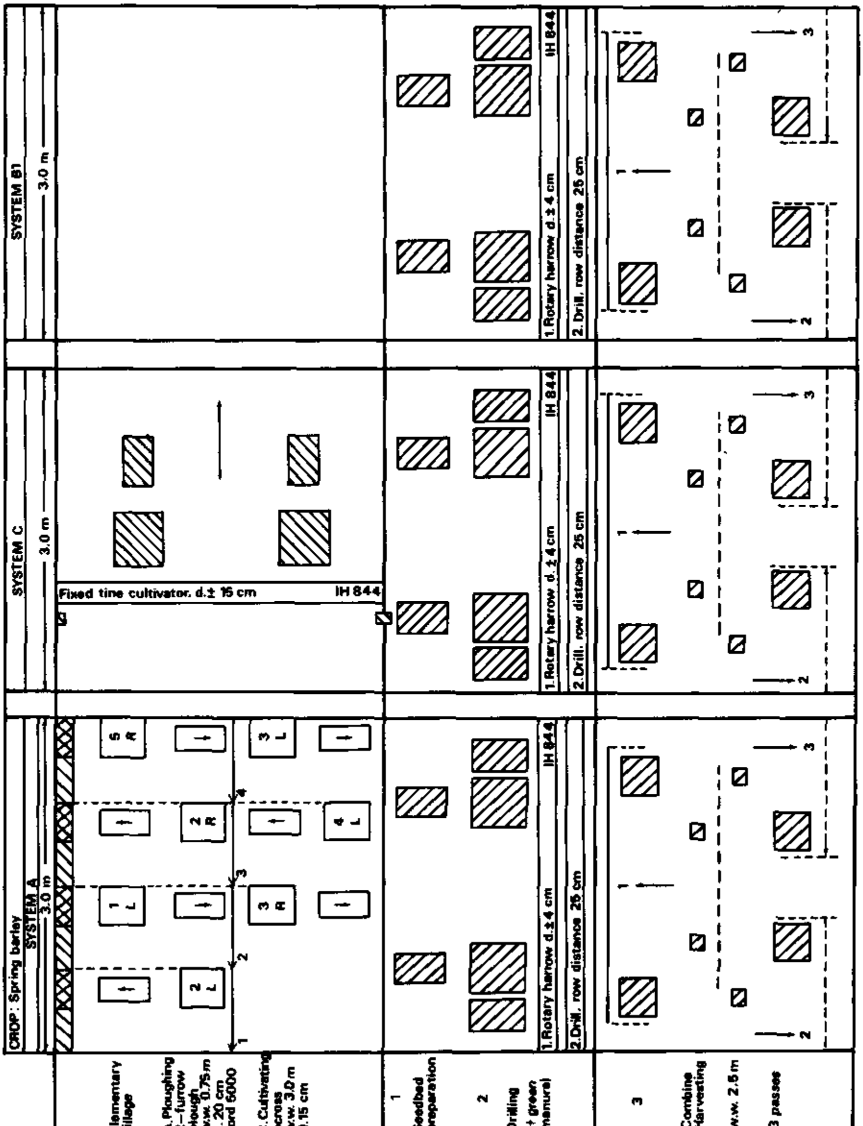

Fig. 7 Driving pattern for spring barley.

Table 6. Tractors and tyres used[a].

Tractor	Tyre size		Tyre width (outline) (m)		Loaded radius (m)		Inflation pressure (bar)	
	front (in)	rear (in)	front	rear	front	rear	front	rear
Ford 5000 (+ front loader)	7.50 16	12-36	0.21	0.30	0.36	0.75	2.0	1.5
Int. Harvester 844 S	12/10 24	14 34	0.27	0.44	0.51	0.76	1.9	1.5
Twin wheels		12-38		0.30	-			
Massey Ferguson 35	6.00 19	9-36	0.16	0.25	0.37	0.66	1.7	1.6
Massey Ferguson 155	7.50-16	12-36	0.21	0.29	0.38	0.71	2.0	1.5
Twin wheels	-	12 36		0.29	-			
Narrow wheels	-	9 36		0.25	-			
Combine cereal harvester	13-24	7.0 12	0.36	0.16	0.55	0.30		

a. The specification of trade marks is for the readers' convenience only. It does not imply any selection or recommendation.

Table 7. Wheel load of tractors and equipment used.

Tractor	Tractor weight (kg)	Load on wheels (kg)		Wheel contact area (cm^2)		Contact pressure (kPa)	
		front	rear	front	rear	front	rear
Ford 5000 (+ frontloader	3270	1420	1850	1000	1400	71	66
I.H. 844 S	3705	1455	2250	1200	2200	61	51
Twin wheels	3960	1460	2500	1200	4000	61	31
M.F. 35	1580	640	940	400	750	80	63
M.F. 155	2210	875	1335	800	1000	55	67
Twin wheels	2315	875	1440	800	2000	55	36
Combine cereal harvester[a]	4155	3365	790	900	1320	187	30

a. Carrying capacity of 300 kg excluded.

Table 8. Working width, weight and weight distribution of drawn implements used.

	Working width (m)	Weight (kg)	Weight distribution
Primary tillage			
2 furrow reversible plough	0.75	580	Load on furrow-wheel 1000 - 1200 kg; contact pressure ≥ 100 kPa.

Table 8. (continued)

	Working width (m)	Weight (kg)	Weight distribution
7-body skim plough	1.75	550	–
Fixed-tine cultivator	3.00	510	–
Fertilizing			
Fertilizer drill	3.00	480	–
Seedbed preparation and ridging			
Spring-tine cultivator	3.00	400	–
Rotary cultivator	3.00	1220	–
Rotary harrow	3.00	755	–
Sowing and planting			
Drill	3.00	550	–
Planter	3.00	600	–
Harvesting			
Potato harvester	1.50	5600	Load on left wheel, 2700 kg, on right wheel 2600 kg; contact pressure 200 and 190 kPa, respectively.
Sugar beet harvester (empty)	0.50	2540	When loaded with 1500 kg, maximum load on left wheel 1600 kg, on right wheel 1980 kg, contact pressure 130 and 170 kPa, respectively.
Trailer (tandem-axle; empty)	–	2665	When loaded with 10 000 kg, maximum load on front wheels of the tractor 980 kg, on rear wheels 4930 kg; contact pressure 40 and 100 kPa respectively.

2.3 Field traffic

2.3.1 Potatoes

In Systems A and C, primary tillage consists of ploughing. In System A, a reversible two-furrow plough was used, and in each pass (in Fig. 3 indicated by 1, 2, 3, 4, 5,) a width of only about 75 cm is ploughed. The rear tyres of the tractor have a width of 30 cm for ploughing (Table 6) which means that at 75 cm intervals only about 45 cm is free of traffic (60%). It is not exactly clear where the wheel tracks of each year are located: one pass fits in the previous, but the working width is not always exactly 75 cm. On the other hand it is certain that the traffic pattern often includes two wheel passes in each track: the first one over the unploughed soil and the second one, two passes afterwards, in the furrow. As can be seen in Fig. 3 with two-furrow ploughing about 40% of the soil is covered by wheeltracks. In this situation 75% of the dynamic tractor load is on the rear wheels. The wheel in the furrow carries about ¾ of the load on the rear axle, which in this case with the added weight of the plough (partly by hydraulic depth control) amounts to at least 2000 kg. With a tyre contact area (footprint) of 1400 cm^2, this means a pressure on the soil of up to 150 kPa at furrow depth. The tyre grousers have a footprint of only 300 cm^2, so if only the grousers are in contact with the soil, the contact pressure is about 350 – 400 kPa. For the potatoes in System C, the skim plough was used with a working width of about 1.75 m, which means about two passes in each 3 m wide plot. Here only

30% of the soil is covered by wheel tracks.

In System A, plantbed preparation, planting and ridging (with ridging bodies on the planter) was carried out in one pass. Therefore, a rather heavy and powerful tractor with twin wheels was required. The outside wheel passed over the soil in which afterwards a row of potatoes was planted, but the soil pressure was only 31 kPa. The soil pressure of the small front wheels, however, was 61 kPa. This one-pass combined field operation resulted in a traffic intensity of 49%, which is far less than in Systems B1 and C, where the three separate passes resulted in 87% coverage by wheel tracks. Because all traffic followed the same path, fixed at the first pass, 50% of the soil was still free from wheel tracks. In all systems the middle two potato rows of the 3 m wide plots were free from spring traffic (Fig. 3, Table 9)

In all systems the harvest was done in the same way with a two-row, drawn potato harvester (Fig. 4). It was attended by a very intensive field transport with tractor and trailer. The pressure on the soil reached high levels (100 – 200 kPa), which resulted in an intensive pattern of (deep) wheeltracks in which the soil was strongly compacted (Lumkes & Perdok, 1981).

Immediately after harvest, under favourable conditions, the topsoil was loosened and levelled across the field with a spring tine cultivator drawn by a tractor on single rear wheels, as a first step in improvement of soil structure. This operation also mixed the fine loose soil created at potato harvest with the underlying firm part of the topsoil. The tractor thus made a rut pattern of 30 cm wide ruts, alternately at 1.50 and 3 m distance between passes, leaving either 1.20 m or 2.70 m intervals free of wheel ruts. In this operation the position of the wheel ruts was not fixed and it differed from year to year.

Table 9. Relative area (%) covered by wheel tracks during subsequent field operations. In parentheses: relative area (%) free from traffic.

		Tillage system		
		A	C	B1
Potatoes	Primary tillage	40 (60)	29 (71)	
	Seedbed preparation + planting + ridging	49 (51)	87 (50)	87 (51)
	Harvesting	68 (51)	68 (51)	68 (51)
	Total	157	184	165
Winter wheat	Levelling + primary tillage	69 (60)	78 (51)	78 (51)
	Drilling	17 (83)	17 (83)	17 (83)
	Crop control + harvesting	48 (52)	48 (52)	48 (52)
	Total	134	143	143
Sugar beet	Primary tillage	40 (60)	40 (60)	–
	Seedbed preparation + drilling	49 (51)	56 (61)	83 (51)
	Crop control + harvesting	214 (0)	214 (0)	214 (0)
	Total	303	303	297
Spring barley	Levelling + primary tillage	69 (60)	58 (71)	29 (71)
	Drilling	49 (51)	49 (51)	49 (51)
	Crop control + harvesting	48 (52)	48 (52)	48 (52)
	Total	166	155	126

However, following potatoes this was the only cross-wise tillage operation, as all other field work was done length-wise. In Systems A and C the levelling operation was followed by primary tillage for winter wheat.

2.3.2 Winter wheat

In System A, ploughing with a two-furrow mounted plough (working width 75 cm) was combined with drilling. The drill was mounted on the right hand side of the tractor. It has a working width of 1.50 m and drills each second pass of the plough (Fig. 5). Soil pressure and traffic intensity at ploughing were almost the same as with ploughing for potatoes. In Systems B1 and C fixed-tine cultivation (working width 3 m) with a tractor on twin wheels was combined with drilling.

Later in the season, field traffic in the wheat crop was the same for all systems. The grass green manure was drilled in spring with a 3 m wide drill. The combine harvester used was especially developed for experimental fields and had a working width of 2.5 m. The soil pressure reached high levels, up to 190 kPa at full load of the combine. It harvests the middle (net)part of each plot and chops and spreads the straw in the same pass. Afterwards the gross parts of the plots were harvested and then the straw from the middle was picked up again. With this harvest procedure, only 50 – 60 cm in the middle of the plot was free from traffic.

2.3.3 Sugar beet

In System A the sugar beet plots were ploughed in the autumn in the same way as for potatoes and winter wheat. Also in System C, the two-furrow plough was used at a depth of 25 cm. However for each system seedbed preparation in spring was carried out in a different way. In System A, seedbed preparation and drilling were combined in one pass with the drill in a bridge-link (sulky). Because of the large size of the tractor and the tyres needed, only the middle two beet rows in System A were free from seedbed traffic (Fig. 6). However, the twin wheels used on the tractor reduced the soil pressure at seedbed preparation and drilling to only 30 kPa. In Systems B1 and C, seedbed preparation and drilling were carried out in two passes. This made it possible to keep the middle three rows free from traffic. However, at seedbed preparation, the inside wheel passed very close to the row drilled afterwards, especially in System B1. The combination of seedbed preparation and drilling in System A reduced traffic intensity compared to System C, and especially to System B1, where the soil was rolled in an extra pass.

Because the extra passes were on fixed paths, the relative area free from traffic was almost the same for all systems (51 – 61%). In fact, because of the smaller tyres used on the tractor, this area was highest in System C.

The harvest procedure for sugar beet is illustrated in Fig. 4. The beets were harvested with a complete, single-row, harvest system, which was attented by intensive traffic.

2.3.4 Spring barly

In all systems, as soon as possible after sugar beet harvest, the top 5 cm of the soil was levelled and loosened by driving across the field with a spring-tine cultivator (Fig. 4). In

System C, primary tillage was carried out with a fixed-tine cultivator to a depth of 15 cm, also across the field (Fig. 7). In System A, primary tillage in the autumn was carried out by ploughing to a depth of 25 cm, as for all other crops in this system. In spring, seedbed preparation and sowing were done in one pass. Because it was thought wise, in most years also in Systems B1 and C seedbed preparation and sowing were combined. The harvest procedure was the same as for winter wheat.

2.4 Discussion

In the 3 m wide nitrate sub-plots, the traffic was more or less fixed. Machinery was selected on this width. Thus traffic intensity was higher than in common practice, because there wider implements can be used for several operations. Although the harvest operation in this experiment was carried out very carefully, relatively high soil pressures could not be avoided and also a very narrow rut pattern had to be accepted.

The intended looser soil structure in System A compared with System C was not attained (Chapter 3). As was explained above, this is understandable from the traffic pattern and related traffic intensity. By ploughing with a two-furrow plough and one tractor wheel in the furrow a large part of the load is transferred to this wheel. This results in a high soil pressure (150 kPa) at furrow depth, which is one reason for the ploughpan found here. Ploughing with a two-furrow plough furthermore includes a pass each 75 cm, which is not the case with the three or four-body plough currently used in practice. By combining field operations in System A, although it reduces the number of passes, requires a heavier tractor, especially in spring. With single wheels this usually results in a higher soil pressure, whereas with twin wheels the area covered by wheel ruts increases. In both cases this has a negative effect on soil structure. As shown in the figures, the type of traffic and the intensity are not favourable for keeping the soil in a loose condition. Only in the very middle of the plot is there a small strip with less traffic. In System A, traffic intensity was increased by using the two-furrow plough, when compared to System C (Table 9). The combined field operations in System A, however, reduced the number of passes and the cumulative area covered by wheels. Because a heavy tractor on twin wheels was used, it did not reduce the area free from any traffic, however.

2.5 Conclusions

The traffic pattern described in this chapter interfered negatively with the intentions of an optimal management of soil structure. Because of the relatively heavy traffic in System A, the intended differences in soil structure, between System A (loose-soil husbandry) and System C (rational tillage) were for an important part not attained. Loose-soil husbandry does not seem possible without some kind of bed culture of permanent traffic system.

Especially Table 9 shows that combining field operations, using rather heavy tractors on twin wheels, is less effective than was initially expected. Figs. 3 - 7 show that the no-till concept in System B1 is far from ideal with the intensive driving pattern practised, because the small dimensions of the plots lead to a fixed traffic pattern.

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3 Soil Structure

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3.1 Methods

Generally, core sampling in the 2 - 7, 12 - 17 and 22 - 27 cm soil layers was performed twice a year: in spring for all crops (after sowing or planting) and in late summer for cereals (after harvest), and sugar beet and potatoes (prior to harvest). However, in late summer 1976, due to a prolonged drought, the soil was so dry that core sampling was impossible. In System B2, in late summer, seed grass and field beans plots were always too dry for core sampling. Because it was not practicable to sample trafficked and untrafficked parts of the plots separately, core sampling was carried out at random. With the aid of the intact 100 cm^3 core samples, total pore space and moisture and air content, both in a field-moist condition and at a pressure potential of -10 kPa (pF 2.0), were determined.

Core samplings were always accompanied by measurements of the penetration resistance with a recording penetrometer (60° cone; 3.84 or 1.86 cm^2 base) to 35 cm depth, and by visual estimation of soil structure, on a scale from 1 (very poor) to 10 (very good), to 20 cm depth (De Boodt et al., 1967).

The outer and inner shape of the potato ridges were measured with a reliefmeter about one month after the last ridging. At the same time the amount of clods >40 and >20 mm diameter in the loose soil of the ridges was determined.

Core sampling and the determination of dimensions and quality of the potato ridges were only carried out on Repetition I. However, measurements of penetration resistance and visual soil structure estimations were carried out on all three repetitions. All measurements were replicated at least 10 times within the sampling site.

On several occasions air permeability was measured according to Kmoch (1961) at pressure potentials of -3 kPa (pF 1.5) and -10 kPa (pF 2.0), using commercially available equipment. In 1978 and 1979, oxygen diffusion coefficients at pressure potentials of -3 and -10 kPa were determined in undisturbed core samples of 230 cm^3, according to a modification (Boone, 1976) of the method proposed by Bakker & Hidding (1970).

3.2 Results

3.2.1 The overall effect of tillage

Tillage had a considerable positive effect on total pore space (Table 10). Compared with non-tilled soil it amounted to, on average, 3.8, 6.2 and 3.7% (v/v) in the 2 - 7, 12 - 17 and 22 - 27 cm layers, respectively. In the 12 - 17 and 22 - 27 cm layers the effect was clearly larger than observed during the first four years of the experiment (Table 11;

Table 10. Effect of tillage and no-tillage on seasonal mean pore space (%, v/v) averaged for all crops, 1976 - 1979.

Year	Tilled (A, C)			Non-tilled (B1, B2)		
	2 - 7 cm	12 - 17 cm	22 - 27 cm	2 - 7 cm	12 - 17 cm	22 - 27 cm
1976	47.3	46.7	44.7	42.0	40.5	42.1
1977	47.4	46.4	45.1	43.4	40.5	41.4
1978	47.1	46.0	45.1	43.7	40.1	41.2
1979	47.1	46.4	45.9	44.3	39.8	41.2
Mean	47.2	46.4	45.2	43.4	40.2	41.5

Table 11. Effect of tillage and no-tillage on seasonal mean pore space (%, v/v), averaged for all crops.

	Depth (cm)	Tilled (A, C)	Non-tilled (B1, B2)	Difference
1972 - 1975	2 - 7	45.8	42.6	3.2
	12 - 17	45.1	41.6	3.5
	22 - 27	44.5	42.6	1.9
1976 - 1979	2 - 7	47.2	43.4	3.8
	12 - 17	46.4	40.2	6.2
	22 - 27	45.2	41.5	3.7

Boone & van Ouwerkerk, 1980). Obviously, this is due both to an increased pore space on tilled soil and to a further decrease in pore space on non-tilled soil in these layers (Fig. 8). In the 2 – 7 cm layer, pore space was increased both on tilled and untilled soil, on the latter owing to seedbed preparation (System B1) and, probably, structure regeneration enhanced by organic matter accumulation (System B2). Therefore, in this layer the difference in pore space with tilled soil remained about the same as in the period 1972 - 1975.

In spring, after seedbed preparation for sugar beet and potatoes, a clear increase in pore space was found as compared with the situation prior to ploughing in autumn (Table 12). In the 22 - 27 cm layer the increase (1.5%, v/v) was about the same as in the period 1972 - 1975 (1.1%, v/v) but in the 2 – 7 and 12 – 17 cm layers the increase (2.1 and 2.0%, v/v, respectively) was much larger than in the period 1972 - 1975 (-0.3 and 0.7%, v/v, respectively).

Probably, the larger mean seasonal pore space found in the period 1976 - 1979 is related to the fact that in this period relatively dry autumns prevailed, whereas in the period 1972 - 1975 the autumns were relatively wet, which negatively affects the loosening effect of primary tillage (Table 13; van Ouwerkerk & Pot, 1978).

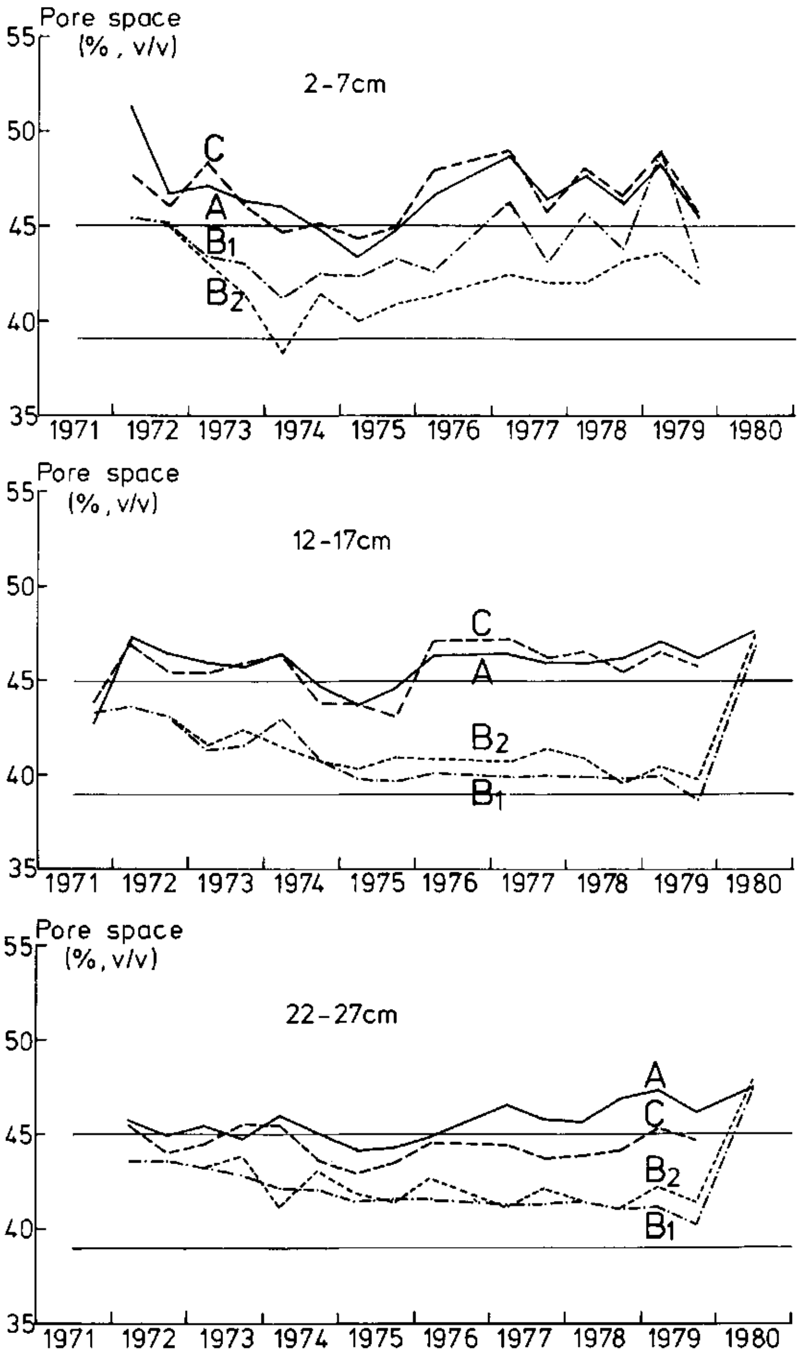

Fig. 8. Pore space during 1972 – 1979, averaged for all crops. Horizontal line at 45% (v/v) pore space: lower boundary of good soil structure; horizontal line at 39% (v/v) pore space: maximum compaction. A = loose-soil husbandry; C = rational tillage; B1, B2 = no-tillage, with and without root crops, respectively.

Table 12. Effect of ploughing for sugar beet and potatoes on pore space (%, v/v), 1975 – 1976, 1977 – 1978 and 1978 – 1979[a].

	2 – 7 cm	12 – 17 cm	22 – 27 cm
Autumn (after cereal harvest)	45.6	44.8	44.0
Spring (after sowing sugar beet and planting potatoes)	47.7	46.8	45.5
Increase	2.1	2.0	1.5

a. In autumn 1976 the soil was too dry for core sampling.

Table 13. Precipitation (mm) in Weeks I – IV prior to primary tillage (autumn) and seedbed preparation for potatoes and sugar beet (spring).

	Period	I + II	III + IV	Total
1972 – 1975	autumn	23.0	54.9	77.9
	spring	9.7	30.2	39.9
1976 – 1979	autumn	16.2	18.8	35.0
	spring	19.9	30.8	50.7

3.2.2 Overall effects of the three tillage systems

When considering the tillage systems separately, it appears (Table 14) that in the regularly tilled layers (2 – 7 and 12 – 17 cm) of Systems A and C mean pore space was similar. Also from data on visual estimation of soil structure in the 0 – 20 cm depth, no consistent differences between these tillage systems could be assessed (Table 15).

In both systems, as an effect of seedbed preparation, pore space in the 2 – 7 cm layer was somewhat larger than in the 12 – 17 cm layer (Table 14). The smaller pore space in the 22 – 27 cm layer of System C demonstrates that the loosening effect of ploughing to a depth of 25 cm once in four years (for sugar beet) disappears rather quickly in subsequent years.

Table 14. Mean ($\bar{x}$)† and mean standard deviation ($\bar{s}_x$)†† of (a) pore space (%, v/v), (b) moisture content at pF 2.0 (%, w/w) and (c) air content at pF 2.0 (%, v/v), averaged for all crops, 1976 – 1979.

Depth (cm)	Loose-soil husbandry (A)			Rational tillage (C)			No-tillage with root crops (B1)			No-tillage without root crops (B2)		
	a	b	c	a	b	c	a	b	c	a	b	c
$\bar{x}$ 2 – 7	47.0	23.3	14.1	47.4	23.4	14.5	44.7	23.9	9.7	42.3	23.5	6.2
12 – 17	46.3	23.5	12.7	46.4	23.6	12.6	39.8	21.3	5.5	40.5	21.6	6.3
22 – 27	46.1	24.4	11.2	44.4	23.3	9.8	41.1	22.1	6.3	41.7	22.2	7.2
$\bar{s}_x$ 2 – 7	3.0	0.9	4.5	3.0	0.7	4.6	2.8	1.2	3.5	1.9	1.3	1.7
12 – 17	3.0	1.4	3.9	3.1	1.4	4.0	1.7	0.8	1.6	1.5	0.8	1.5
22 – 27	2.7	1.5	3.3	2.6	1.1	3.6	1.6	0.8	1.8	1.8	0.8	2.1

† n = 280, †† n = 28.

Table 15. Mean visual estimation of soil structure (units in a scale from 1 (very poor) to 10 (very good)[a]), 1976 1979.

Depth (cm)	Loose-soil husbandry (A)	Rational tillage (C)	No-tillage with root crops (B1)	No-tillage without root crops (B2)
0 - 10[b]	7	7	6+	5½
10 - 20	6+	6	4	4½

a. n = 280.

b. Except for potatoes.

Table 16. Effect of tillage depth on pore space (%, v/v) in spring, 1976 - 1979.

	2 7 cm	12 - 17 cm	22 - 27 cm
Cultivator[a] (10 15 cm)	48.8	46.1	43.6
Plough[b] (15 cm)		47.4	44.4
Plough[c] (25 cm)	47.8	46.7	46.1

a. System C (winter wheat and spring barley).

b. System C (potatoes).

c. System A (all crops) and System C (sugar beet).

The effect of tillage depth on pore space is further demonstrated in Table 16. In the 22 - 27 cm layer ploughing to a depth of 25 cm resulted in a larger pore space as compared to ploughing to a depth of 15 cm or cultivating to a depth of 10 - 15 cm. In the 12 - 17 cm layer ploughing to a depth of 15 cm produced a somewhat larger pore space than fixed-tine cultivation, of which the effective working depth varied between 10 and 15 cm. However, in the 2 - 7 cm layer, probably due to a stronger crumbling effect, fixed-tine cultivation resulted in a larger pore space than ploughing.

In Systems B1 and B2, the 12 - 17 and 22 - 27 cm layers were non-tilled and, therefore, had a much smaller pore space than in Systems A and C (Table 14), especially in the 12 - 17 cm layer, because of compactive effects of field traffic. In the 2 - 7 cm layer pore space was much larger than in deeper layers; in System B1 because of seedbed preparation, and in System B2 because of the combined effect of a higher organic matter content (Chapter 5) and the presence of surface mulch. It is remarkable that, although statistically not significant, there was a tendency that in the 12 - 17 and 22 - 27 cm layers, System B1 had a still smaller pore space than System B2. Compaction during root crop harvest under sometimes bad soil conditions seems a reasonable explanation for this tendency. From the linear positive relationship between mean pore space and mean standard deviation of pore space (Fig. 9) it can be concluded that non-tilled soil is clearly more homogeneous than tilled soil.

It should be noted that in Table 14 the results of spring and autumn core samplings were averaged. However, core sampling for cereals was carried out after harvest, at which the tilled soil was compacted, especially in the 2 - 7 cm layer (Table 17). Therefore, for tilled soil, pore space during the growing season of cereals was higher than indicated in Table 14.

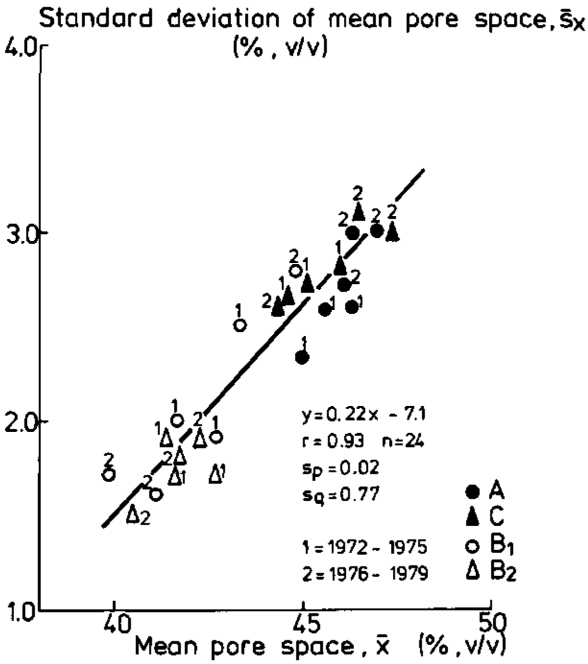

Fig. 9. Relationship between mean pore space and the standard deviation of mean pore space, averaged for all crops, 1972 - 1979. A = loose-soil husbandry; C = rational tillage; B1, B2 = no-tillage, with and without root crops, respectively.

By and large, differences in water content at pF 2.0 (Table 14) were similar to those in the first four years of the experiment. Again, water content at pF 2.0 was influenced by water content prior to sampling (Fig. 10). In non-tilled soil, accumulation of organic

Table 17. Mean pore space (%, v/v) in spring and in autumn (after harvest) on plots with winter wheat and spring barley, 1977 - 1979.

Depth (cm)	Period	A	C	B1	B2
2 - 7	spring	47.6	48.8	48.4	42.8
	autumn	44.9	45.2	43.4	42.5
	decrease	2.7	3.6	5.0	0.3
12 - 17	spring	46.7	46.0	40.3	40.8
	autumn	44.8	44.6	39.5	40.2
	decrease	1.9	1.4	0.8	0.6
22 - 27	spring	46.5	43.8	41.6	41.5
	autumn	45.0	43.2	40.6	41.4
	decrease	1.5	0.6	1.0	0.1

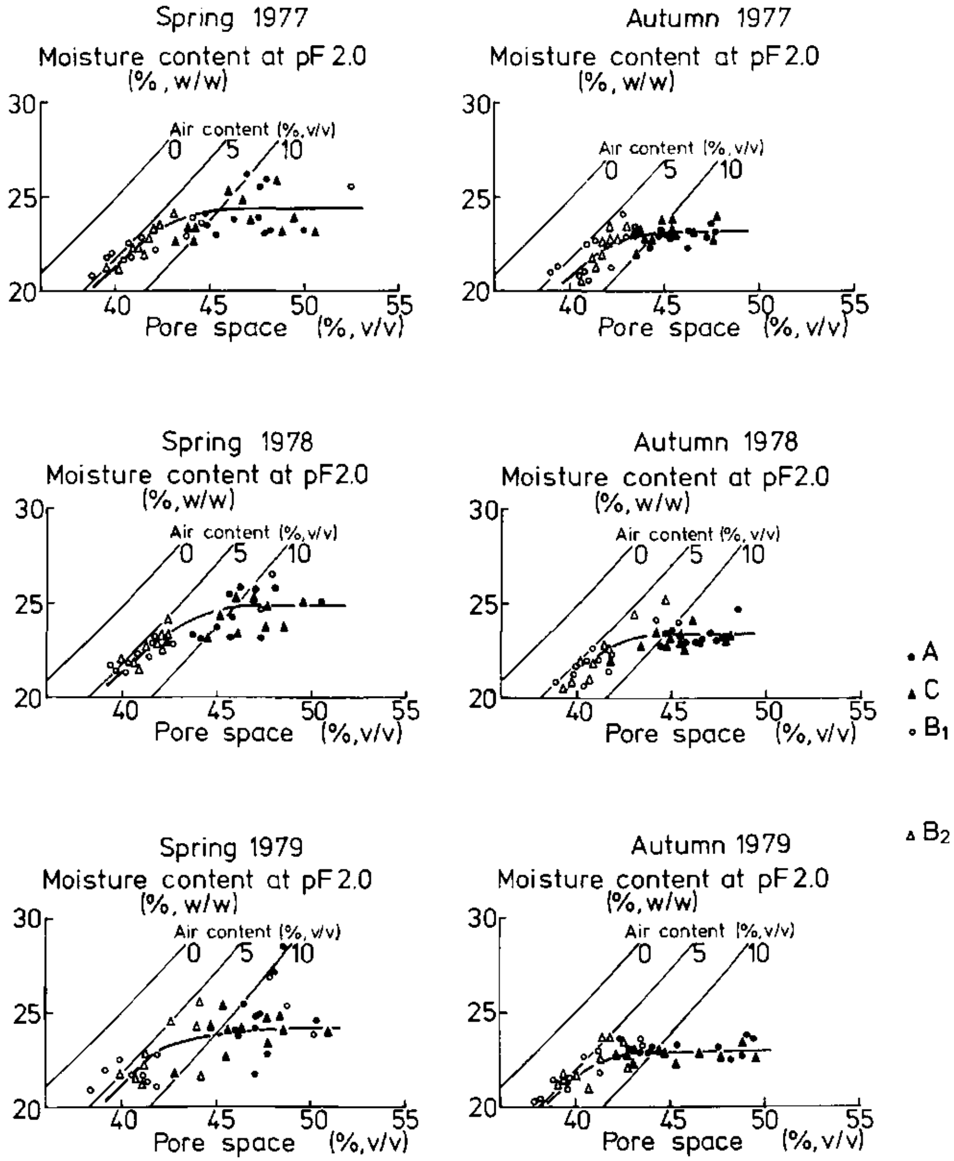

Fig. 10. Relationship between mean pore space and moisture content at pF 2.0 in spring and in autumn in 1977, 1978 and 1979. A = loose-soil husbandry; C = rational tillage; B1, B2 = no-tillage, with and without root crops, respectively.

matter at the surface increased moisture content at pF 2.0 in the 2 – 7 cm layer such that it was similar to the moisture content in tilled soil (Table 14). Finely crumbled soil sieved out at potato harvest that remained near the surface and seedbed preparation for other crops (System B1) increased the moisture content at pF 2.0 still further. However, in the dense 12 - 17 and 22 - 27 cm layers of both Systems B1 and B2, water content at pF 2.0 was clearly lower than in the tilled soil.

Deeply buried organic debris and green manure crops in loose-soil husbandry increased the water content of the 22 - 27 cm layer at pF 2.0. Because fresh organic material decomposes rather rapidly, this effect disappeared in the course of the growing season: compared with System C, the difference was much larger in spring (1.4%, w/w) than in autumn (0.6%, w/w).

Fortunately, wet conditions during harvesting of root crops and during subsequent tillage operations, which causes soil structure deterioration and increases water content at pF 2.0, did occur less frequently during the second rather than during the first crop rotation (Table 13).

Air content at pF 2.0 on tilled soil generally decreased with depth, due to decreasing pore space and increasing moisture content at pF 2.0. In non-tilled soil air content at pF 2.0 was significantly lower than in tilled soil. The difference was even larger than during the first four years of the experiment because pore space in tilled soil was now larger, whereas in non-tilled soil it was smaller (Table 11). However, it should be stressed again that, due to the lower water content at pF 2.0, the differences in air content were smaller than might be expected from the differences in pore space. On average, air content at pF 2.0 was 10 - 15% (v/v) in tilled and 5 - 7% (v/v) in non-tilled soil layers.

3.2.3 Effects of tillage systems in different crops

Between the loose-soil husbandry and rational tillage systems there were some small but consistent differences in soil structure. These differences related to differences in depth and intensity of tillage as practiced for different crops.

Potatoes With loose-soil husbandry, pore space in the 12 - 17 cm layer was about the same as with rational tillage, but pore space of the 22 - 27 cm layer was 2.3% (v/v) larger (Table 18). This difference may be regarded as a direct effect of ploughing to a depth of 25 cm instead of 15 cm.

Winter wheat Pore space in the 2 - 7 cm layer was 2% (v/v) larger with rational tillage than with loose-soil husbandry. This is due to the fact that with fixed-tine cultivation at 10 - 15 cm depth most of the finely crumbled soil sieved out at potato harvest remains near the surface, whereas with ploughing to about 25 cm depth it is turned in deeply. In the 12 - 17 cm layer, soil structure on loose-soil husbandry and rational tillage were similar. In the 22 - 27 cm layer System A had a 3.2% (v/v) larger pore space and a 1.1% (v/v) higher moisture content at pF 2.0, which is a direct effect of ploughing to a depth of 25 cm instead of fixed-tine cultivation to a depth of 10 - 15 cm.

Sugar beet In both systems ploughing depth was 25 cm. Hence, pore space was also about the same in the 22 - 27 cm layer. From the similar pore space in the 2 - 7 cm layer and from the somewhat smaller pore space in the 12 - 17 cm layer of System A, it may be concluded that combination of field operations in spring did not result in a looser soil.

Spring barley Due to compaction during the harvest of sugar beet, in both systems the

Table 18. Mean[†] pore space (a), moisture content at pF 2.0 (b), air content at pF 2.0 (c) and visual estimation of soil structure (d), 1976 1979[††].

Crop	Depth (cm)	Loose-soil husbandry (A)				Rational tillage (C)				No-tillage with root crops (B1)				No-tillage without rootcrops (B2)			
		a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
Potatoes	2 7		-		8½	-		-	8+		-	-	7½	42.0	22.9	6.6	5+
(B2: grass)	12 - 17	46.8	23.1	14.0	7–	47.2	23.7	13.9	6	39.9	21.3	5.8	4–	40.4	21.0	6.9	4+
	22 27	46.8	24.4	12.2		44.5	23.3	10.2	-	41.1	21.9	6.7		41.8	21.7	8.1	-
Winter wheat	2 7	45.8	23.0	12.6	7	47.8	23.3	15.3	7	46.4	24.2	11.9	7–	42.5	23.5	6.5	5½
	12 17	46.8	23.7	13.2	6+	46.0	23.2	12.5	6½	40.0	21.3	5.8	5	40.8	21.6	6.6	4½
	22 - 27	46.2	23.8	12.0		43.0	22.7	8.5	-	41.2	22.2	6.5	-	41.8	22.2	7.4	-
Sugar beet	2 - 7	48.1	23.4	15.7	7+	47.7	23.2	15.4	7+	44.0	23.4	8.9	6	42.0	23.4	5.8	5+
(B2: beans)	12 17	46.5	23.7	12.8	6+	47.4	24.0	13.7	6	39.0	21.2	4.6	3½	40.7	21.8	6.2	4½
	22 - 27	46.5	24.7	11.2	-	46.1	24.1	11.6		40.8	22.2	5.9	-	41.8	22.5	6.9	-
Spring barley	2 - 7	47.1	23.6	13.9	7	46.7	23.8	12.9	7–	44.3	24.2	8.6	6	42.5	23.8	6.1	5½
	12 - 17	45.1	23.4	10.8	6	45.0	23.7	10.3	5½	40.1	21.5	5.9	4	40.3	21.6	5.9	4+
	22 - 27	45.0	24.5	9.3	-	43.9	23.2	9.2		41.3	22.3	6.4	-	41.5	22.2	6.9	

[†] n = 70; data for grass and field beans refer to spring samplings only (n = 35).

[††] a = %, v/v; b = %, w/w; c = %, v/v; d = units in a scale from 1 (very poor) - 10 (very good).

12 - 17 cm layer had a smaller pore space than with any other crop. The low pore space and the relatively high moisture content at pF 2.0 in the 22 - 27 cm layer of System A may be caused by turning under the smeared toplayer by ploughing to 25 cm depth. In System C, the soil was tilled with a fixed-tine cultivator to a depth of 10 - 15 cm, and pore space in the 22 - 27 cm layer was about the same as found in winter wheat and potatoes. This means that no significant after-effect of ploughing to 25 cm depth for sugar beet was found.

With no-tillage pore space was always smallest in the 12 - 17 cm layer, and soil structure in the 12 - 17 cm and 22 - 27 cm layers did not differ much for different crops. However, because in System B1 a seedbed was prepared for all crops, the 2 - 7 cm layer had a considerably larger pore space than in System B2. This was especially true for winter wheat because, when shallow cultivating after potato harvest, most of the finely crumbled soil remains at or near the surface.

3.2.4 Soil structure changes in the course of time

Owing to better soil conditions during primary tillage (Table 14), tilled soil had a larger mean pore space during the second crop rotation than during the first crop rotation (Fig. 8). At cereal harvest, pore space in the 2 - 7 cm layer of all systems in which a seedbed was prepared (Systems A, B1 and C) decreased sharply, due to compaction. Also in the 12 - 17 and 22 - 27 cm layers of System A and in the 12 - 17 cm layer of System C there was a clear negative effect of compaction on mean pore space (Table 17).

In the course of time, differences in mean pore space between loose-soil husbandry and rational tillage were nearly absent in the 2 - 7 cm layer and inconsistent in the 12 - 17 cm layer. Because with loose-soil husbandry the depth of the main tillage treatment was significantly larger in three out of four years, especially during the second crop rotation, pore space in the 22 - 27 cm layer was significantly larger than with rational tillage.

During the second crop rotation, in System B1 mean pore space of the 2 - 7 cm layer was not as large as in Systems A and C, because after sowing sugar beet in System B1 the loose seedbed was compacted with a Cambridge roller. However, during the second crop rotation there was a general trend that in this layer mean pore space in both Systems B1 and B2 increased in the course of time. Probably this can be explained by a further accumulation of organic matter in the topsoil (Chapter 5).

During the first three years of the experiment, pore space in the 12 - 17 cm layer gradually decreased; in the second crop rotation there was no general trend. However, in nearly all cases System B1 had a somewhat smaller pore space than System B2. There are indications that this was caused by harvesting root crops under very wet soil conditions in 1974. In subsequent years the difference in pore space between both systems was quite stable, indicating that further compaction in this layer can take place only under very extreme conditions. In the 22 - 27 cm layer differences in pore space between Systems B1 and B2 were only small.

It can already be stated (although this does anticipate Chapter 14) that, surprisingly, at the end of the experiment ploughing to a depth of 25 - 28 cm of plots tilled each year and plots untilled for eight years gave similar pore spaces for the full depth of the ploughed layer (Fig. 8).

3.2.5 Shape and quality of potato ridges

The mean cross-sectional area of the loose soil of the 75 cm spaced ridges usually was clearly smaller with loose-soil husbandry than with both other systems (Table 19). However, variations between years were quite large (Table 20).

The year 1976 was the first year with a generally good soil structure after several years of disappointing results and, compared with the standard size of 600 – 750 cm^2 (Kouwenhoven & van Ouwerkerk, 1978), potato ridges were very large in all systems. In 1977 and 1978, the cross-sectional area of the ridges in System A was 32% smaller than in 1976 because at greater depths the soil was too wet to build up a larger ridge in the one pass that is allowed in this system. Because the spring of 1978 was quite wet, the usual inter-row rotary cultivation in Systems B1 and C could not be carried out as deeply as necessary to obtain enough loose soil. Consequently, the cross-sectional area of the ridges was 26% (System B1) and 36% (System C) smaller than in 1976 and 1977.

On average, external shape of the ridges did not differ much between tillage systems (Fig. 11). On rational and no-tillage plots the ridges were 8° steeper, wheras the top was

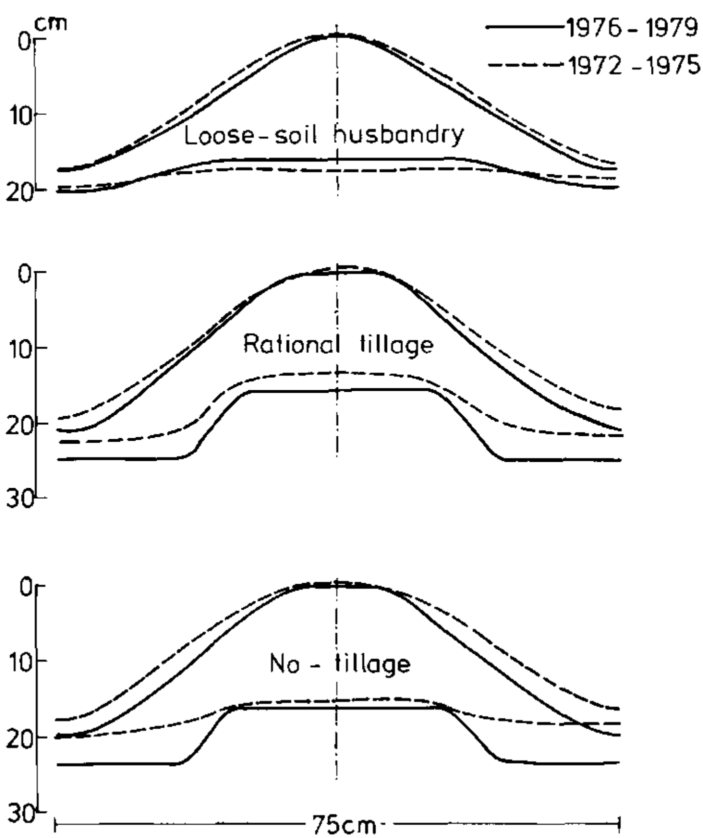

Fig. 11. Mean cross-section of potato ridges during 1972 – 1975 and 1976 – 1979.

Table 19. Mean shape and quality of potato ridges, 1976 – 1978.

System	Depth of loose layer (cm)	Cross-section (cm^2)	Distance top ridge to firm soil (cm)	Width at 5 cm below the top (cm)	Slope halfway up (°)	Clods (%, w/w)	Visual estimation of soil structure (units)[a]
A (loose-soil husbandry)	8.4	631	16	24	31	6	8½
C (rational tillage)	10.6	798	15	26	40	7	8+
B1 (no-tillage)	10.5	784	16	26	38	7	7½

a. Units in a scale from 1 (very poor) – 10 (very good).

Table 20. Characteristics of potato ridges.

	Loose-soil husbandry (A)				Rational tillage (C)				No-tillage (B1)			
	1976	1977	1978	1979	1976	1977	1978	1979	1976	1977	1978	1979
Depth of loose layer (cm)	10.7	7.3	7.3	.	13.1	11.1	7.8	.	11.9	11.0	8.4	.
Cross-section (cm^2)	803	545	544	.	982	831	582	.	895	825	633	.
Distance from top ridge to firm soil (cm)	20	14	15	.	16	17	14	.	18	16	15	.
Clods (%, w/w) >20 mm	3.0	8.9	6.3	.	7.6	5.9	6.0	.	11.2	5.3	3.6	.
>40 mm	0.0	1.7	1.5	.	0.0	0.3	0.7	.	0.0	0.1	0.0	.
Visual estimation of soil structure in spring (units)[a]	8½	8+	8½	9	8+	8+	8½	8½	7+	7+	8	7½

a. Units in a scale from 1 (very poor) – 10 (very good).

flatter. Without inter-row rotavation (System A) the boundary between the loose soil in the ridge and the firm soil underneath was nearly flat but, with inter-row rotary cultivation shortly after planting, in both Systems B1 and C a pronounced plateau was created. In the 1972 – 1975 period the plateau was much less pronounced, probably because of drier soil conditions during inter-row rotary cultivation, preventing deep penetration of the inter-row rotavator. Consequently, in spite of the differences in cross-sectional area, the mean distance between the seed potatoes (planted at about 1 cm above the firm soil) and the top of the ridges usually was about the same for all systems.

In Systems A and C the quality of the potato ridges, as judged by visual estimation of soil structure and by the amount of clods, was very good and did not differ much between systems. However in System B1, the clods created by rotary cultivating of dense untilled soil were more angular, smoother and less porous and were therefore scored lower on visual assessment.

3.2.6 Cone resistance

Resistance to penetration depended heavily on pore space, but also moisture content had a strong effect, especially at low pore spaces (Fig. 12). Because non-tilled soil not only has a clearly lower pore space but also a lower moisture content at pF 2.0, even at field capacity resistance to penetration is much higher than on tilled soil. For root development this may be a serious drawback (Chapter 8 and 9) but for trafficability it is a big advantage.

The relationship between pore space and resistance to penetration was similar for the periods 1972 – 1975 and 1976 – 1979, and was not significantly different for tilled and non-tilled soil. It may be concluded that, generally, resistance to penetration on non-tilled soil will always be 2 – 3 times as large as on adjacent tilled soil.

3.2.7 Visual estimation of soil structure

The relationship between the visually estimated quality of soil structure and total pore space was linear (Fig. 13) and rather strong ($r=0.81$). The straight line found in the period 1972 – 1975 was on a slightly lower level and had a slightly steeper slope. However, in both periods there was a wide scatter and, therefore, both lines do not differ significantly.

It can be concluded that visual estimation of soil structure may give a fair estimate of the differences in pore space between tilled and non-tilled soil. The critical score, 5½, corresponds with a pore space of about 44% (v/v), which agrees with the critical air content of about 10% (v/v), which marks the transition between loose and compacted soil (Fig. 10).

3.2.8 Air permeability

Air permeability (K_i) is a complex but very sensitive indicator of macro-porosity. In contrast to gas diffusion, mass flow of gas is strongly dependent on the radius of the air-filled pores. At compaction the largest pores disappear first and, therefore, K_i of untilled soil is lower than of tilled soil (Table 21). If $K_i = 10^{-8}$ cm^2 is considered to be at

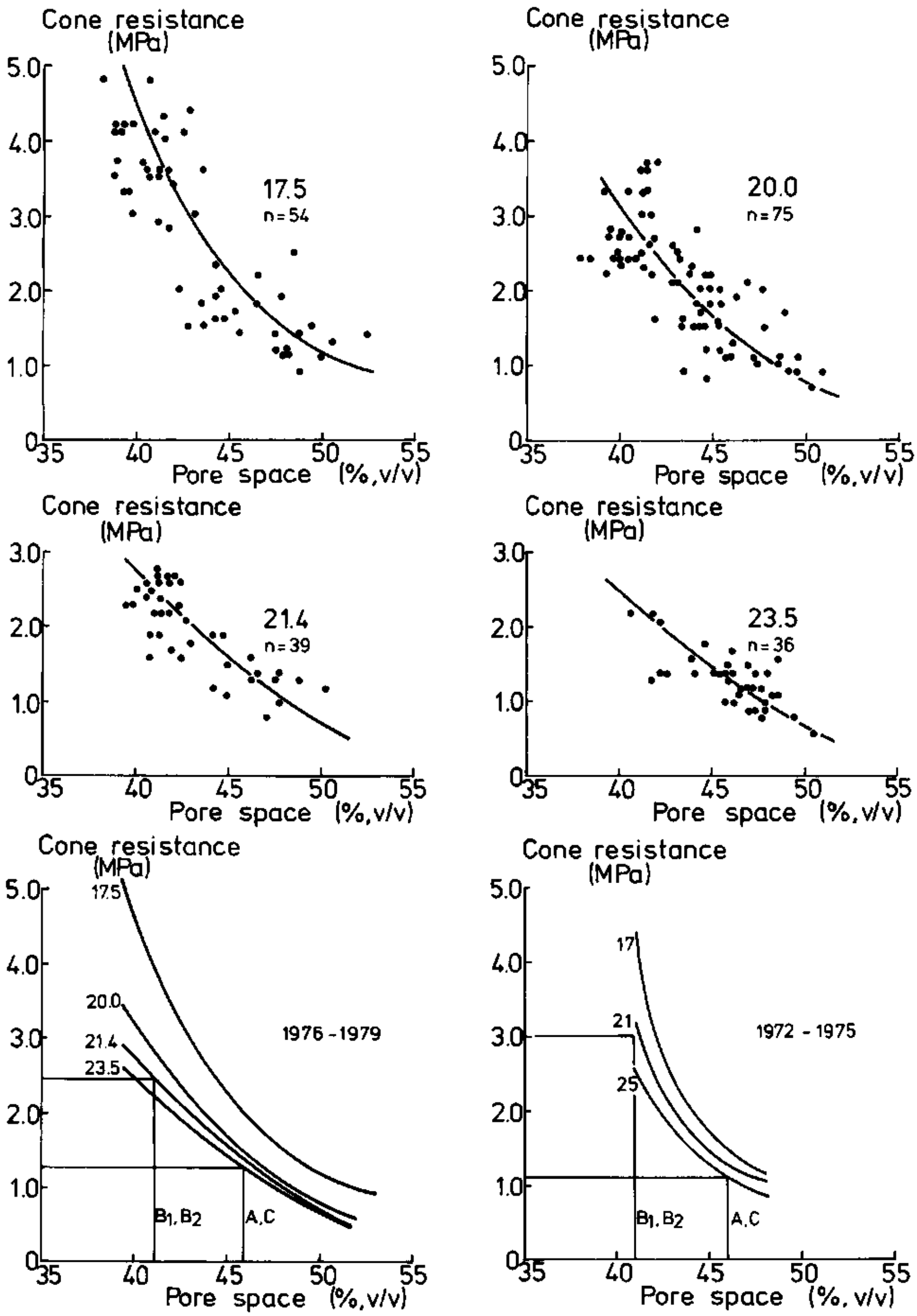

Fig. 12. Relationship between pore space and resistance to penetration at moisture contents of 17.5, 20.0, 21.4 and 23.5% (w/w), respectively, 1976 - 1979. Bottom right: the same relationschip for the period 1972 - 1975 (Boone & van Ouwerkerk, 1980).

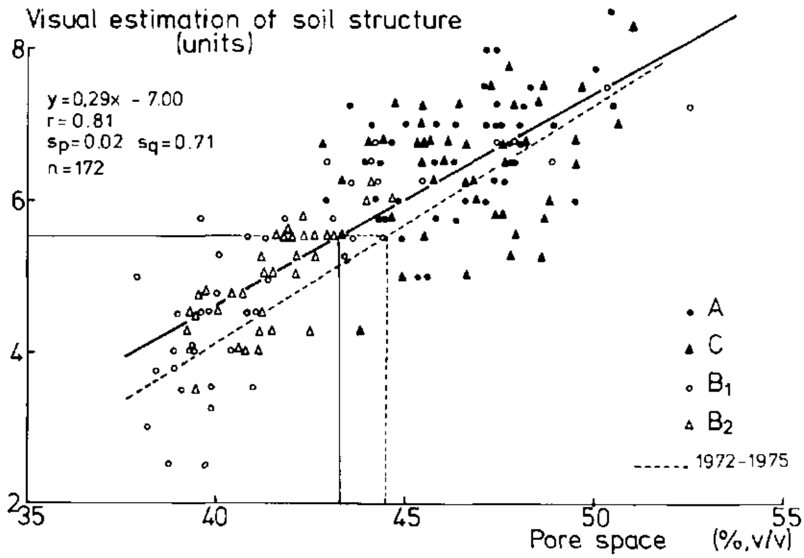

Fig. 13. Relationship between visually estimated soil structure and pore space, 1976–1979. A = loose-soil husbandry; C = rational tillage; B1, B2 = no-tillage, with and without root crops, respectively.

the transition from a fairly low to a medium high permeability (O'Neal, 1949), it appears that usually also on untilled soil mean air permeability was reasonable, even at pF 1.5.

After a very wet autumn and winter, soil structure was very bad in spring 1975, but in spring 1976 pore space of most of the tilled plots was again at a normal level and did not increase further in later years (Fig. 8). Nevertheless, K_i was highest in the last two years of the experiment (Table 21). In System B1 air permeability was even lower in 1976 than in 1975. This observation indicates that, both on tilled and untilled soil, regeneration of soil

Table 21. Mean air content (A: %, v/v) and air permeability (K_i: 10^{-8} cm²) in the 12–17 cm layer at soil water potentials of −3 kPa (pF 1.5) and −10 kPa (pF 2.0).

Year	Crop	Loose-soil husbandry (A)				No-tillage with root crops (B1)				No-tillage without root crops (B2)			
		pF 1.5		pF 2.0		pF 1.5		pF 2.0		pF 1.5		pF 2.0	
		A	K_i	A	K_i	A	K_i	A	K_i	A	K_i	A	K_i
1975	potatoes	.	.	7.8	19	.	.	5.7	2	.	.	5.9	3
	winter wheat	.	.	6.2	3	.	.	5.6	2	.	.	5.8	3
	sugar beat	.	.	6.4	2	.	.	3.7	0.5	.	.	6.6	4
	spring barley	.	.	5.9	5	.	.	6.3	1	.	.	.	.
1976	sugar beet	8.7	3	10.8	7	3.5	<0.1	4.9	0.7	.	.	.	.
	potatoes	12.2	19	14.5	29	4.0	<0.1	4.7	0.2	.	.	.	.
1978	spring barley	12.4	42	15.0	86	4.4	5	6.6	7	2.6	1	4.9	2
1979	spring barley	13.1	25	15.4	42	3.9	2	5.2	5	5.7	3	7.4	5

structure takes longer than one year. Because in System B2 there were no root crops, soil structure had not deteriorated in autumn 1974 and K_i did not increase in the course of the second crop rotation.

The relationship $K_i = a\,\epsilon_g^{\,b}$ between air permeability (K_i: cm^2) and air content (ϵ_g: v/v) was clearly different for tilled and untilled soil (Table 22; Fig. 14). The correlation was very good for tilled soil (System A) and usually reasonable but sometimes poor for untilled soil (Systems B1 and B2). Fig. 14 shows that at the same low air content (e.g. 5%, v/v) air permeability on untilled soil would be similar or even higher than on tilled soil.

3.2.9 Gas diffusion coefficient

From theoretical considerations (Currie, 1961) it may be concluded that the gas diffusion coefficient D_s ($cm^2\,s^{-1}$) and air content ϵ_g (v/v) are related by $D_s = a\,\epsilon_g^{\,b}$. Indeed, for the 12 - 17 cm layer of System A very good and for Systems B1 and B2 fair correlations were found (Table 23).

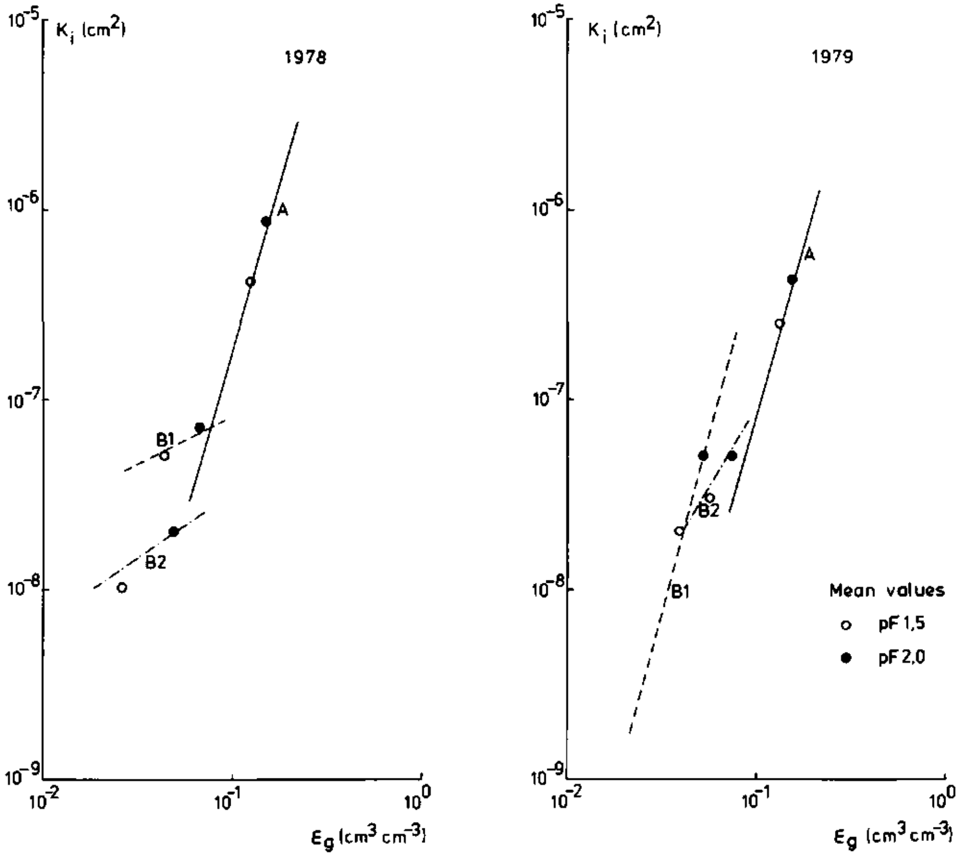

Fig. 14. Relationship between air permeability (K_i) and air content (ϵ_g) in the 12 - 17 cm layer of spring barley plots in 1978 and 1979. Lines are restricted to the range measured. A = loose-soil husbandry; C = rational tillage; B1, B2 = no-tillage, with and without root crops, respectively.

Table 22. Mean pore space (P: %, v/v), coefficients a and b†, and correlation coefficient (r) between air permeability (K_i: cm^2) and air content (ϵ_g: v/v) in the 12 - 17 cm layer of spring barley plots in 1978 and 1979.

Year	Loose-soil husbandry (A)				No-tillage with root crops (B1)				No-tillage without root crops (B2)			
	P	a	b	r	P	a	b	r	P	a	b	r
1978	47.0	1.13×10^{-3}	3.783	0.95	40.2	2.61×10^{-7}	0.512	0.35	39.8	1.67×10^{-7}	0.711	0.60
1979	47.2	1.80×10^{-4}	3.242	0.96	39.1	4.85×10^{-3}	3.889	0.87	42.5	5.18×10^{-6}	1.767	0.53

† $K_i = a\, \epsilon_g^{\,b}$.

Table 23. Mean pore space (P: %, v/v), coefficients a and b†, and correlation coefficient (r) between gas diffusion coefficient (D_s: $cm^2\,s^{-1}$) and air content (ϵ_g: v/v) in the 12 - 17 cm layer of spring barley plots in 1978 and 1979.

Year	Loose-soil husbandry (A)				No-tillage with root crops (B1)				No-tillage without root crops (B2)			
	P	a	b	r	P	a	b	r	P	a	b	r
1978	47.0	0.583	2.515	0.946	40.2	0.034	1.245	0.822	39.8	0.013	1.056	0.722
1979	47.2	0.129	1.874	0.931	39.1	0.050	1.340	0.669	42.5	0.151	1.914	0.750

† $D_s = a\, \epsilon_g^{\,b}$.

System A had a considerably higher mean gas diffusion coefficient than Systems B1 and B2 (Table 24). Averaged for 1978 and 1979, at a soil water potential of −3 kPa (pF 1.5), D_s of System A was 4.6 times, and at a soil water potential of −10 kPa (pF 2.0) 4.4 times, higher than in System B1. Differences between Systems B1 and B2 were not consistent between years, but on average in System B1, D_s was higher than in System B2 by 1.6 times (pF 1.5) and 1.4 times (pF 2.0), respectively.

It is remarkable that at air contents lower than 10% (v/v), D_s would be higher on non-tilled soil than on tilled soil (Fig. 15). Differences between tilled and untilled soil were larger for System B1 than for System B2. For both years, at pF 1.5, mean D_s of Systems B1 and B2 was 2.4 and 2.2 times higher, respectively, and at pF 2.0, 1.8 and 1.3

Table 24. Mean air content (A: %, v/v) and gas diffusion coefficient (D_s: 10^{-4} cm^2 s^{-1}) in the 12 – 17 cm layer of spring barley plots in 1978 and 1979, at soil water potentials of −3 kPa (pF 1.5) and −10 kPa (pF 2.0).

Year	Loose soil husbandry (A)				No-tillage with root crops (B1)				No-tillage without root crops (B2)			
	pF 1.5		pF 2.0		pF 1.5		pF 2.0		pF 1.5		pF 2.0	
	A	D_s	A	D_s	A	D_s	A	D_s	A	D_s	A	D_s
1978	13.0	38.5	16.0	58.1	5.1	8.4	7.2	12.8	3.1	3.3	5.4	6.0
1979	12.9	27.6	15.1	37.5	3.7	6.0	4.9	8.8	5.5	5.9	7.2	9.9

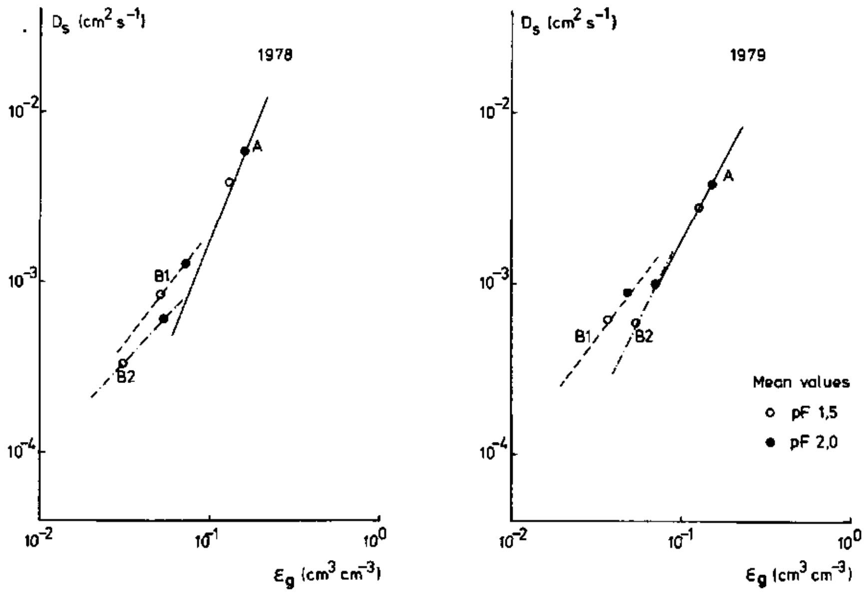

Fig. 15. Relationship between gas diffusion coefficient (D_s) and air content (ϵ_g) in the 12 – 17 cm layer of spring barley plots in 1978 and 1979. Lines are restricted to the range measured. A = loose-soil husbandry; C = rational tillage; B1, B2 = no-tillage, with and without root crops, respectively.

times higher, respectively, than System A would probably have at the same air content.

It can be calculated that when in a 30 cm thick soil layer with a very high oxygen consumption (10^3 mg m^{-2} h^{-1}), the oxygen concentration should not decrease below 10% (v/v), the gas diffusion coefficient should equal $D_s = 3 \times 10^{-3}$ cm^2 s^{-1}. This gas diffusion coefficient can be regarded therefore as a safe upper critical limit. When in the same soil layer the oxygen consumption is 10 times lower (10^2 mg m^{-2} h^{-1}) and the oxygen concentration is allowed to decrease to 1% (v/v), a 20 times lower critical limit of $D_s = 1.5 \times 10^{-4}$ is permitted. However, in most conditions this value of D_s results in a fully insufficient aeration.

Using these criteria for D_s, it may be concluded that the tilled soil will always have an adequate aeration, even at pF 1.5. In the non-tilled soil the situation is clearly different. Nevertheless, at high soil water pressures, values of D_s are well above the earlier mentioned minimum level, and at pF 2.0 half way between the upper and lower critical limits. This means that only under wet soil conditions, combined with a fairly high oxygen consumption, problems with the macro gas transport may be expected. In that case, at the bottom of the arable layer, low or very low oxygen concentrations will be found. In Chapters 8 and 9 this matter will be treated in greater detail.

3.3 Discussion

Soil structure encountered in the field is determined by soil, climatic and biological factors, but also by technological factors, of which the tillage system is an integral part (Boone & van Ouwerkerk, 1980). Eight years of research in tillage systems made it clear that a large complex of factors indeed has to be considered. It also revealed that results obtained with respect to soil structure can be explained by and large if the relevant characteristics of the tillage system are known.

Not only the tillage treatments practiced for a particular crop, but also the crop rotation and at least the tillage treatments practiced for the previous crop, have to be taken into account. Although crop rotation and tillage systems were fixed, soil structure in loose-soil husbandry and rational tillage was clearly better during the period 1976 – 1979 than during the period 1972 – 1975. This is explained by the difference in soil conditions at the time subsequent parts of the tillage systems were applied in both periods (Fig. 16).

Soil conditions have an important influence on the compactive and puddling effects of harvest operations as well as on the loosening effects of the subsequent main tillage operation. Wet conditions at potato harvest and especially at sugar beet harvest induce soil structure deterioration. Then, because late in the season evaporation is low, quite often the main tillage operation also has to be carried out under wet soil conditions. As a consequence, soil structure is not improved to the same extent as under more normal, drier conditions. This occurred especially in the excessively wet autumn and early winter of 1974/1975. However, owing to favourable weather conditions, soil structure already regenerated during the 1975 growing season and, in Systems A and C, was further improved in the autumn of 1976, when primary tillage could be carried out under dry soil conditions. As indicated by increased air permeability, soil structure regeneration continued in subsequent years. However, in Systems B1 and B2, especially in the 12 – 17 cm layer, pore space and air content at pF 2.0 remained at a very low level.

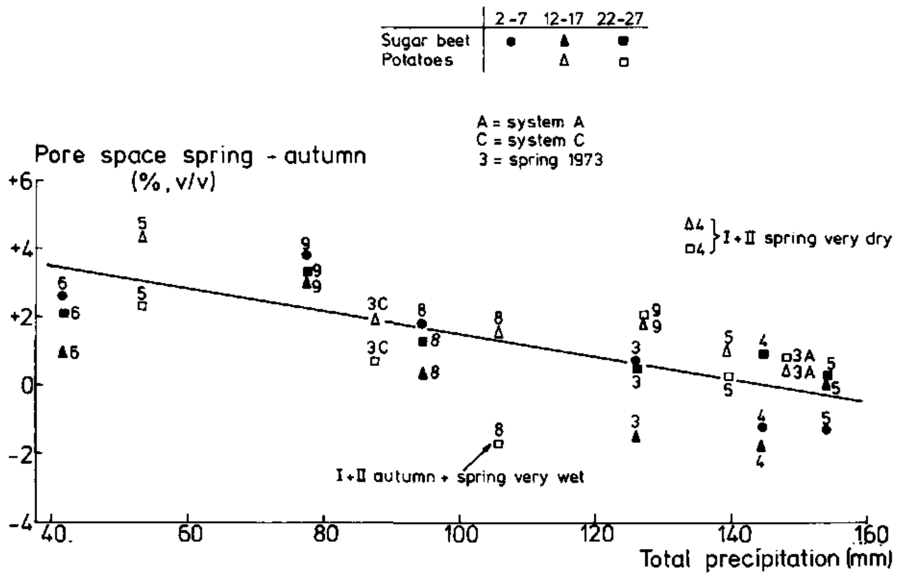

Fig. 16. Relationship between total precipitation in Weeks I/IV before primary tillage and seedbed preparation, and the combined effect of primary tillage and seedbed preparation for potatoes and sugar beet on total pore space, relative to total pore space before primary tillage, averaged for Systems A and C.

It was to be expected that during 1976 – 1979 loose-soil husbandry and rational tillage would result in a larger difference in soil structure than during 1972 – 1975 because the difference in the technological content of these tillage systems was now larger, especially with respect to tillage depth. However, differences in soil structure found were only small, perhaps because soil conditions at harvest of root crops and during subsequent primary tillage operations were more favourable than during the period 1972 – 1975.

Differences between secondary tillage treatments in loose-soil husbandry and rational tillage had an important effect on seedbed quality (Chapter 4), but not on soil structure below the seedbed. Combination of field operations as performed in loose-soil husbandry, did not therefore have the intended effect. Several factors may be held responsible for this result. Firstly, although the area compacted in loose-soil husbandry was reduced as much as possible, due to the dimensions of the tyres of the heavy tractor and the relatively small working width of the conventional machinery used, it still constituted a considerable proportion of the total area (Chapter 2). Secondly, haphazard driving over the field, as is quite common on farmer's fields (Håkansson, 1965) and which should thus have formed part of the rational tillage system as practiced here (progressive farmer's system), was largely absent. Although the main plots were 30 m wide, the nitrogen subplots had a width of only 3 m, which was the width of all implements used and, therefore, field traffic was also more or less controlled in the rational tillage system.

Thus, it did not matter much whether seedbed preparation and sowing were combined (loose-soil husbandry) or carried out in separate passes (rational tillage). These combinations even had some drawbacks with respect to the execution of the sowing operation, as is discussed in Chapter 4. It may be concluded that in loose-soil husbandry field traffic can only be further reduced by the use of much wider implements and wide-axle tractors with (semi) permanent traffic lanes. However, it is still questionable if these complex systems may be economical for the common arable farming practice (Lamers, 1982).

On tilled soil, compactive effects at harvest were quite strong. Therefore, in rational tillage, the 20 - 25 cm layer, which was loosened only once in four years by ploughing to 25 cm depth for sugar beet, was by the next crop (spring barley) already nearly as dense as before. Non-tilled soil had even in the first growing season (1972) a clearly smaller pore space than tilled soil. Although harvest operations on untilled soil had a much smaller effect, pore space gradually decreased further during the next two years. However, since the root crop harvest in the very wet autumn of 1974, which caused a sharp decrease, pore space remained rather stable.

The dense non-tilled soil was more homogeneous and had a better trafficability than tilled soil. Pore space in the most compacted part of the arable layer, i.e. at about 15 cm depth, was close to the minimum value to be expected under prevailing conditions (van Ouwerkerk, 1976). Therefore, with common machinery, further compaction at this depth is not to be expected and at other depths only at harvest conditions worse than in the autumn of 1974. However, in the period 1976 - 1979 a slow but gradual improvement of soil structure of the top layer was observed, which probably was related to the accumulation of organic matter (Chapter 5). The platy structure of this layer, which in the first years of the experiment was characteristic for untilled soil, became also gradually less pronounced. At greater depth the soil had a compact, massive appearance that could, however, be broken relatively easily into many angular, smooth-edged clods and aggregates. Measurements of gas diffusion and air permeability also pointed to a slightly improved continuity of the system of big(ger) pores. This topic is discussed in greater detail in Chapters 8 and 9.

3.4 Conclusions

1. In the period 1976 - 1979, soil structure of tilled soil was clearly better than in the period 1972 - 1975. Probably this is related to drier soil conditions in autumn, which decreased the compacting effects of harvest operations and increased the loosening effect of subsequent primary tillage. On untilled soil, after the first three years of the experiment (1972 - 1974), no further decrease in total pore space was observed in the 12 - 17 and 22 - 27 cm layers. In the top layer, total pore space increased slightly, which was related to organic matter accumulation and/or seedbed preparation. On untilled soil, with common machinery, further compaction at greater depths can only be expected during harvest operations at soil conditions even more vulnerable to compaction than during the very wet autumn of 1974.

2. Soil structure, damaged by harvest operations under wet conditions in the autumn of 1974, could be considerably improved by performing primary tillage in 1975 under favourable soil moisture conditions. Nevertheless, measurements of air permeability indicated that in subsequent years soil structure was further improved.

3. In regularly tilled layers, loose-soil husbandry did not create a looser soil structure than rational tillage because, technologically, rational tillage already was quite sophisticated. Moreover, due to practical limitations (narrow subplots), the results obtained in

loose-soil husbandry could not be improved.

4. Again, it appeared that soil moisture content at a soil water potential of - 10 kPa (pF 2.0) is not a constant value. It was positively affected by a high water content during a prolonged period prior to sampling, by a high amount of finely crumbled soil, and by fresh organic material. It was negatively affected by a small pore space, as found in untilled soil.

5. On average, in tilled soil at a soil water potential of - 10 kPa (pF 2.0), air content was about twice, and the gas diffusion coefficient about 4 times, as high as in untilled soil. However, at small air contents (< 10%, v/v) the gas diffusion coefficient was slightly higher on untilled than on tilled soil. This indicates that pore continuity of the big(ger) pores was better on untilled than on tilled soil. In untilled soil, problems with the macro gas transport may be expected only under wet soil conditions (pF 1.5), combined with a rather high oxygen consumption.

6. On untilled soil resistance to penetration at a soil water potential of - 10 kPa (pF 2.0) was already 2.5 MPa and it increased sharply at decreasing soil moisture contents. Moreover, the number of big pores was relatively small and pore continuity probably only slightly improved. Therefore, in a dry growing season, root growth may encounter serious difficulties in untilled soil.

7. Generally, potato ridges of adequate size and quality could be established in all three tillage systems. However, in wet springs it was not possible to build sufficiently large ridges in one pass, as in loose-soil husbandry, because at the greater working depth required the soil was still too wet. In the no-tillage system, and especially in the rational tillage system, inter-row rotary cultivation shortly after planting produced a pronounced internal plateau, which sometimes caused extra clod formation at harvest. Rotary cultivation of untilled soil (full-width and inter-row) created clods that were more angular, smoother and less porous than in tilled soil. Due to wetter soil conditions during inter-row cultivation, the plateau was more pronounced in the second than in the first crop rotation.

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4 Timing of field work and effect of primary and secondary tillage

C. van Ouwerkerk & L.M. Lumkes

4.1 Timing of field work

4.1.1 Post-harvest cultivations

Directly after sugar beet and potato harvest, in all systems the plots were levelled by working the soil transversely with a spring-tine cultivator to a depth of 5 – 7 cm.

After cereals, in System B1 the green manure grass, volunteer plants and couch grass were killed with glyphosate. After spring barley, in System C the green manure grass was killed with paraquat, because here ploughing depth for potatoes was only 15 cm, which is insufficient to cover the grass completely. In System A and in System C after winter wheat, no such killing of green manure grass was necessary as it could be incorporated into the soil by ploughing to 25 cm depth. Killing the green manure grass was always performed about 2 months after cereal harvest to allow the grass to develop well.

In System B2, after seed grass harvest the stubble was burnt after killing the regrowth with glyphosate. After field beans, glyphosate was applied to kill weeds and grass.

4.1.2 Primary tillage

In System A (loose-soil husbandry) the main tillage treatment for all crops was always ploughing to 25 cm depth. In System C (rational tillage) ploughing was performed for root crops only. For sugar beet ploughing depth was the same as in System A (25 cm), but for potatoes it was much less (15 cm). For cereals in System C, primary tillage consisted of fixed-tine cultivation to about 15 cm depth (i.e. depth of the chisel points; the effective depth of loosening usually is about 5 cm less). For winter wheat, fixed-tine cultivation was always carried out length-wise, but for spring barley, in 1976 – 1978, to reduce wheelslip, the fixed-tine cultivator was pulled across the field (Chapter 1). In System B1 no primary tillage was performed, except for winter wheat where (after potatoes) the soil was tilled with a fixed-tine cultivator to a depth of 5 – 6 cm to restore contact with the dense subsoil and to increase the amount of coarse clods at the surface.

Due to favourable weather conditions (Fig. 17) primary tillage could always be carried out between mid-October and mid-November, which is very favourable for this type of soil.

To ensure that winter wheat was sown in the second half of October, when it preferably should, primary tillage for this crop was performed between one (1975) and four (1978) weeks earlier than for the other crops, except in the very dry autumn of 1976 when for all crops primary tillage was carried out very early (mid-October).

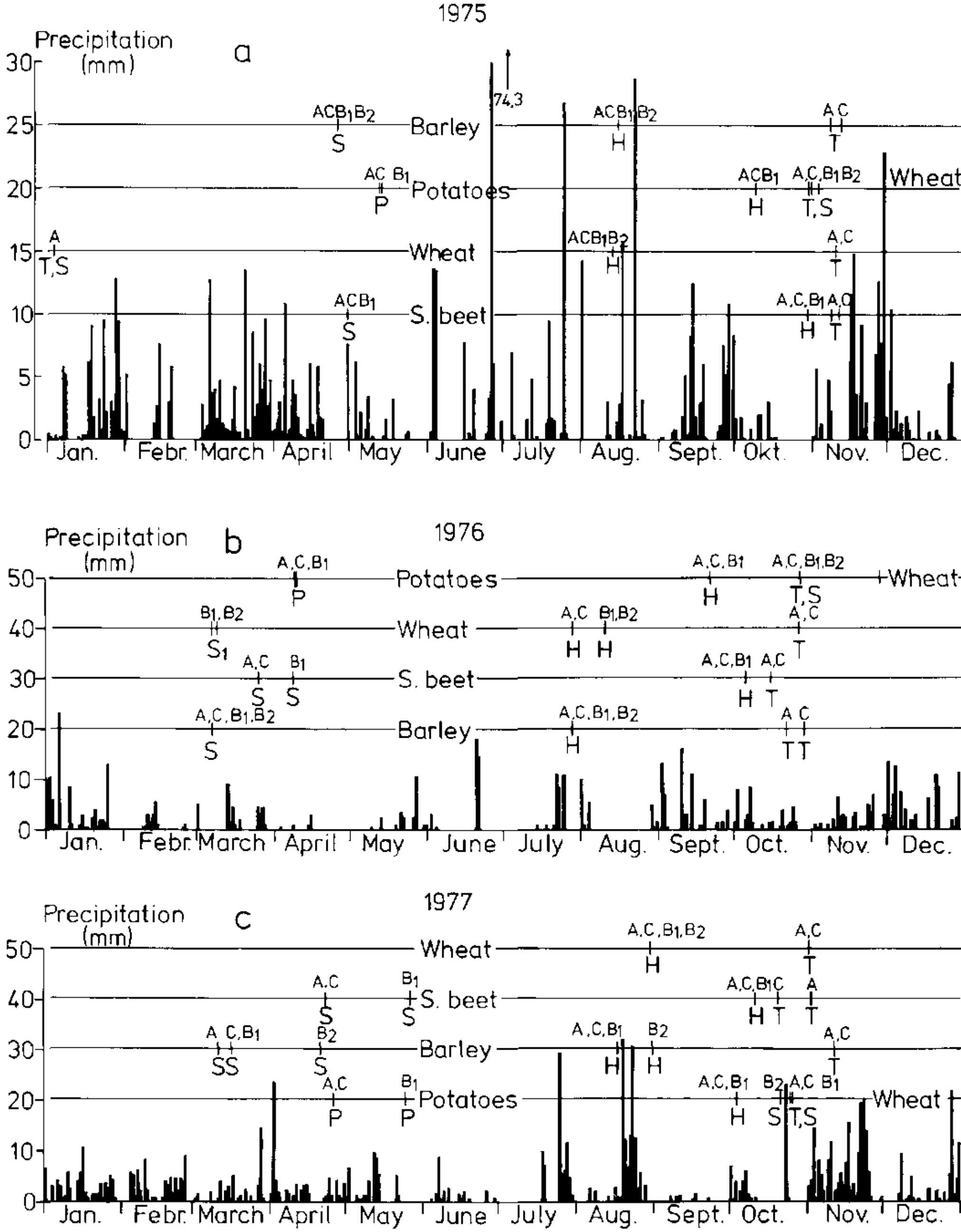
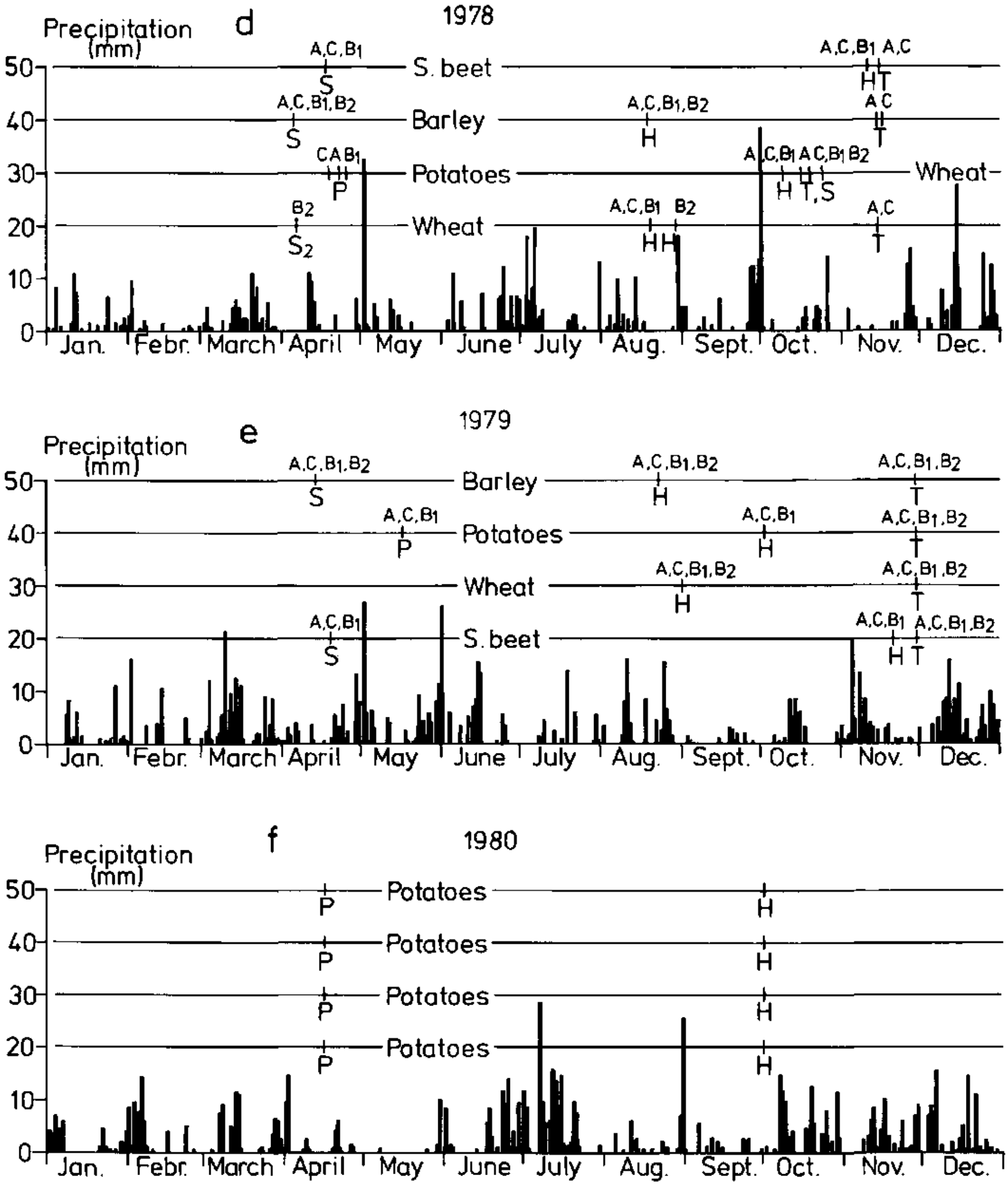


Fig. 17. Timing of field work. A = loose-soil husbandry; C = rational tillage; B1 = no-tillage with root crops; B2 = no-tillage without root crops; T = primary tillage; S = seedbed preparation and/or sowing; S1 = resowing; S2 = additional sowing; P = plantbed preparation and/or planting; H = harvest.


d
1978
Precipitation (mm)
S. beet
Barley
Potatoes
Wheat
Wheat
A,C,B1
S
A,C,B1,B2
S
CAB1
P
B2
S2
A,C,B1,B2
H
A,C,B1
B2
H H
A,C,B1
A,C,B1 B2
H
T,S
A,C,B1 A,C
H T
A C
T
A,C
T
e
1979
Precipitation (mm)
Barley
Potatoes
Wheat
S. beet
A,C,B1,B2
S
A,C,B1
P
A,C,B1
S
A,C,B1,B2
H
A,C,B1
H
A,C,B1,B2
H
A,C,B1,B2
T
A,C,B1,B2
T
A,C,B1,B2
T
A,C,B1
H
A,C,B1,B2
T
f
1980
Precipitation (mm)
Potatoes
Potatoes
Potatoes
Potatoes
P
P
P
P
H
H
H
H
0
10
20
30
40
50
Jan.
Febr.
March
April
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.

4.1.3 Secondary tillage and sowing or planting

In System B2, winter wheat and spring barley were sown with a triple-disc drill without any seedbed preparation on approximately the same date as in the other systems.

For winter wheat, secondary tillage was omitted in Systems A, C and B1. Sowing was combined with primary tillage by mounting the seed drill either to the side of the tractor (System A) or to a bridge link (Systems B1 and C). In all cases the seed was harrowed in by spring tines attached to the drill.

For spring barley, in Systems A, C and B1 the rotary harrow was used, except in 1976 when the soil was nicely weathered and the spring-tine cultivator was sufficient. In all systems seedbed preparation was combined with sowing (bridge link), except in 1976 when in Systems B1 and C the soil was allowed to dry for a few hours before sowing in a separate pass.

For sugar beet and potatoes, in Systems A and C the seedbed was prepared with the rotary harrow, except for potatoes in 1976, when in System C the nicely weathered soil permitted planting without any seedbed preparation. In System B1 the full-width rotary cultivator was used, in 1978 and 1979 it was preceded by harrowing to force the topsoil to dry. In System A, sowing was combined with seedbed preparation, although with sugar beet there was some clogging of the seed drill due to still moist, adhering soil. In Systems B1 and C the soil was always allowed to dry for a few hours before sowing or planting in a separate pass. For potatoes in Systems B1 and C row-rotavating + ridging was usually carried out within one week after planting, except in 1977 when in System C one had to wait for nearly one month before the soil had dried enough.

In spring the first crop to drill is spring barley, preferably at the beginning of March. Sugar beet follows some two weeks later and, finally, after another two weeks potatoes are planted.

In 1976, due to very favourable weather conditions this scheme could be followed, except for sugar beet in System B1 where the topsoil was too wet to prepare a seedbed on the same date as in Systems A and C.

In the wet spring of 1977, spring barley was sown on 11 March in System A and on 16 March in Systems B1 and C. In System B2, spring barley was sown one month later than in Systems B1 and C because when these systems were sown the triple-disc drill was not available and, later on, it remained too wet. Due to high rainfall in the beginning of April, sowing of sugar beet had to be postponed until 22 April and planting of potatoes until 25 April. In System B1, again for sugar beet, but now also for potatoes, the soil was then too wet for seedbed preparation and, therefore, these crops could not be sown or planted before 24 May.

In 1978 the month of March was too wet for field activities and, therefore, spring barley could not be sown before 5 April, followed by sugar beet on 17 April and potatoes between 18 and 25 April.

In 1979 again March was a wet month and sowing of spring barley and sugar beet had to be delayed until the middle of April. Heavy rainfall in the end of April and the beginning of May caused excessive delay for potato planting (16 May).

4.1.4 Harvest operations

Harvest time for spring barley is usually by the end of July, and for winter wheat the middle of August. However, due to differences in planting time and seasonal climate, the date the crops reach full maturity may differ from year to year. Moreover, when this stage is reached, weather conditions may be unfavourable for harvesting. The favourable, relatively dry 1976 growing season is reflected in a normal harvest date for spring barley and in an early harvest date for winter wheat in Systems A and C. In Systems B1 and B2, harvest was two weeks later because on 8 March these systems had to be resown with spring wheat.

In 1977 - 1979 both spring barley and winter wheat were harvested in the second half of August. In System B2, in 1977 spring barley harvest was two weeks later due to sowing one month later, and in 1978 winter wheat was harvested 10 days later than in the other systems because System B2 had to be additionally sown with spring wheat on 5 April.

Sugar beet should preferably be harvested before the middle of October, which was the case in 1976 and 1977. Harvest dates in 1978 and 1979 were one month later than in 1976 and 1977, which perfectly reflects the difference in sowing dates between these years. In 1979, sugar beet harvest was extremely late due to very wet conditions at the beginning of November.

Potatoes are best harvested by the end of September or at the beginning of October. Due to favourable weather conditions this could be done in all four years.

4.2 Effect of primary tillage

Except for 1975/1976, directly after primary tillage the direct effect was assessed by visual estimation of soil surface roughness and the degree of crumbling. In spring the degree of soil slaking was visually estimated (Table 25).

4.2.1 Potatoes

Ploughing to 25 cm depth (System A) usually resulted in a coarsely crumbled soil and a rather even surface. Green manure grass could be incorporated nicely into the soil. However, in the very dry autumn of 1976 the soil crumbled too strongly. In System C, by ploughing to 15 cm depth with a 7-body stubble plough the soil was insufficiently inverted and green manure grass was not covered very well. However, soil surface roughness in System C was about the same as in System A.

4.2.2 Winter wheat

In Systems A, C and B1, primary tillage, sowing and harrowing were always carried out in one pass and, therefore, the figures in Table 25 refer to the combined effect. In System A, by ploughing to 25 cm depth the soil was coarsely crumbled but enough fine aggregates were produced to cover the seed. In System C, coarse clods from beneath were mixed into the fine top layer by fixed-tine cultivation to 15 cm depth, but on the whole the seedbed was finer than in System A. In System B1, by fixed-tine cultivation to only 5 cm depth, only few coarse clods were mixed into the top layer, which, therefore,

Table 25. Visual estimation of the results of primary tillage in autumn and of soil slaking in spring.

Crop	Year	Soil surface roughness[a]			Degree of crumbling[b]			Degree of slaking[c]		
		A	C	B1	A	C	B1	A	C	B1
Potatoes	1976/77	6	7−	.	8	8	.	6½	6+	.
	1977/78	8−	7½	.	.	.	.	8½	8	.
	1978/79	8½	8+	.	6½	6+	.	7½	7½	.
	Mean	7+	7½	.	7+	7+	.	7½	7+	.
Winter wheat[d]	1976/77	7	6+	5+	7+	8+	8	7	5	4−
	1977/78	6−	6−	5+	.	.	.	6+	5−	4+
	1978/79	7	6	5	7½	8	9−	7	5½	3−
	Mean	6½	6	5+	7+	8	8+	7−	5	3½
Sugar beet	1976/77	5+	7+	.	8+	7½	.	6+	7½	.
	1977/78	6½	7	.	.	.	.	7	7½	.
	1978/79	7	8−	.	8½	7+	.	6½	7−	.
	Mean	6+	7+	.	8+	7+	.	6½	7+	.
Spring barley	1976/77	7½	6+	.	7+	7	.	7½	6	4−
	1977/78	7−	7−	5½	.	.	.	7	6+	5½
	1978/79	9	9−	6½	6−	6	7	7½	7	5½
	Mean	8−	7+	6	6½	6½	7	7+	6+	5

a. 1 = very smooth; 10 = very rough.
b. 1 = very coarse; 10 = very fine.
c. 1 = completely slaked; 10 = not slaked.
d. After sowing.

remained too fine.

In System B1 the too fine top layer easily slaked and, therefore, in 1979 the stand of the winter wheat was very sparse. However, serious slaking, to the extent that the field had to be resown with spring wheat, occurred only in the autumn and winter of the 1975/1976 season.

4.2.3 Sugar beet

In System A ploughing to a depth of 25 cm means ploughing of annually disturbed, relatively loose soil. Moreover, ploughing was combined with levelling by means of a harrow mounted to the side or to the front of the tractor. The result was a fairly intensively crumbled soil and a level surface. In System C, by 25 cm ploughing the rather dense 15 - 25 cm layer, which was disturbed only once every four years, was coarsely crumbled and deposited on the surface. Moreover, in this system levelling was omitted. Fortunately, therefore, soil surface roughness was always markedly larger than in System A, where it was less than desirable.

4.2.4 Spring barley

Ploughing lengthwise to 25 cm depth (System A) and fixed-tine cultivation across the field to 15 cm depth (System C) resulted in about the same degree of crumbling and in the same soil surface roughness. In both systems, due to soil compaction at sugar beet harvest, soil crumbling was clearly less and soil surface roughness clearly larger than for the other crops.

4.3 Soil slaking during winter

The degree of soil slaking during winter is influenced by the tilth produced by primary tillage and by the amount and distribution of rainfall (Fig. 17). During a wet winter (1978/1979) the soil slakes more than during a dry one (1977/1978). It must be borne in mind, however, that only when the visually estimated value for soil slaking is under 4 may the situation become dangerous for winter wheat growth. This potential danger was always present in System B1 (Table 25), but in fact only in spring 1976 did the crop suffer so badly that it had to be resown. Even then real problems only ocurred in dips, which, however, were abundant.

For the same reason in System B2 in spring 1976 the crop also had to be resown, and in 1978 it had to be additionally sown with spring wheat. For potatoes and sugar beet the soil was ploughed in both Systems A and C, and, therefore, no slaking occurred. For winter wheat and spring barley, slaking was more severe after fixed-tine cultivation in System C than after ploughing in System A, but even in the winter wheat fields the degree of slaking was still above the critical limit.

4.4 Effect of secondary tillage

4.4.1 Potatoes

In System A the working depth at seedbed preparation (8 - 10 cm) was much larger than in System C (about 5 cm), which is reflected in a higher moisture content in the potato ridges directly after planting (Table 26). In System B1 the working depth was about the same as in System C, but here, due to omitting primary tillage, soil moisture content usually was much higher (Fig. 18). In 1976, when the soil was nicely weathered and in System C seedbed preparation could be omitted, also in System B1 workablility was very good. In 1977, however, seedbed preparation in System B1 had to be delayed for about one month. Therefore, in 1978 and 1979 System B1 was harrowed some weeks before seedbed preparation to force the topsoil to dry. However, the effect of this treatment was only small: soil workability remained marginal.

In System B1, due to shallow full-width rotavating, less clods >20 mm were found but because there were also far less aggregates <2.5 mm, mean aggregate diameter was slightly larger than in Systems A and C. Ridges in System A were slightly finer than in System C.

4.4.2 Winter wheat

The differences in seedbed quality between Systems A, C and B1 are illustrated in Table 27. Judged by the dry weight of the biggest clods, seedbed tilth was finest in System B1 and coarsest in System A. The smallest clods had the highest moisture content, but in

Table 28. Characteristics of the seedbed for spring barley and sugar beet, 1978.

	Spring barley	Sugar beet

root crops and cereals, was similar in Systems A, B1 and C, but 17% lower in System B2. Although root crops in Systems A, B1 and C obtained on average 175 kg ha^{-1} of P_2O_5, the maximum difference between root crops and cereals, which occurred in System B1, was only 18 kg ha^{-1} of P_2O_5 (Table 34). In System A the difference was less, and in System C it was even negative.

With root crops, the amount of potassium was smaller in System B2 than in Systems A, B1 and C, which were similar. As could be expected, in System A this amount was somewhat larger for root crops than for cereals. However, in System C equal amounts, and in Systems B1 and B2 clearly smaller amounts, were found. For potatoes, 500 kg ha^{-1} of K_2O was applied, but values found were not higher than after application of 150 kg ha^{-1} of K_2O for sugar beet.

Of the total amount of phosphate (0 – 100 cm), on average 77 and 79%, for root crops and cereals, respectively, was concentrated in the 0 – 30 cm layer. For potassium, these figures were 53 and 55%, respectively. Within the arable layer the distribution of these elements was quite different between systems. In Systems B1 and B2 and more so for root crops than for cereals, most of the phosphate was concentrated in the top 10 cm (Fig. 21) and this amount decreased sharply with depth. In System A the phosphate applied for root crops was ploughed in, which increased the amount of phosphate in the 10 – 20 cm layer. In System C this effect was smaller because for potatoes the soil was ploughed less deeply than in System A. After root crops harvest, ploughing for cereals in System A redistributed the remaining phosphate. In System C with fixed-tine cultivation the uneven distribution with depth was more or less maintained. The amount of phosphate

Table 34. Amount of phosphate (P_2O_5; Pw-method) and potassium (K_2O) in topsoil and subsoil (15 January 1976).

Depth (cm)	Tillage system							
	A		B1		B2		C	
	kg ha^{-1}	rel.	kg ha^{-1}	rel.	kg ha^{-1}	rel.	kg ha^{-1}	rel.
Phosphate root crops[a]								
0 – 30	91	79	93	78	71	75	79	76
30 – 100	25	21	26	22	25	25	26	24
total	116	100	119	100	96	100	105	100
Phosphate cereals								
0 – 30	81	78	80	80	69	78	94	80
30 – 100	23	22	21	20	19	22	23	20
total	104	100	101	100	88	100	117	100
Potassium root crops[a]								
0 – 30	986	52	1105	58	935	52	995	52
30 – 100	906	48	790	42	837	48	907	48
total	1892	100	1895	100	1772	100	1902	100
Potassium cereals								
0 – 30	983	55	1178	56	1109	54	1040	55
30 – 100	831	45	926	44	947	46	869	45
total	1814	100	2104	100	2056	100	1909	100

a. Seed grass and field beans in system B2.

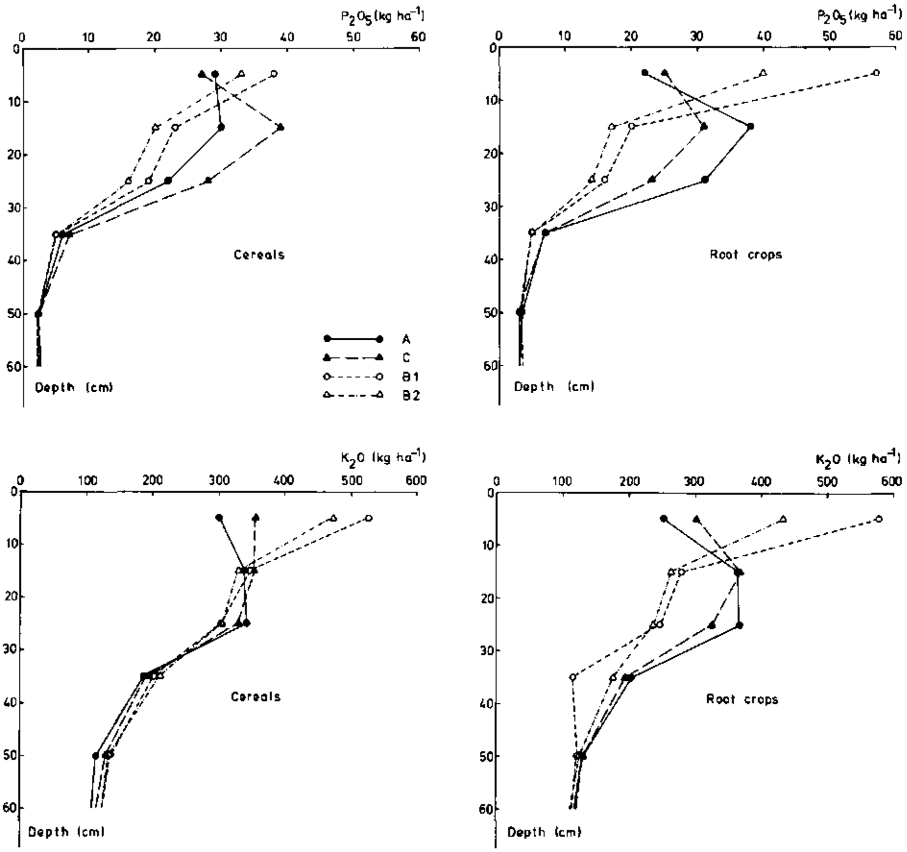


Fig. 21. Distribution with depth of the amount of phosphate and potassium in 10 cm layers on plots to be cropped with cereals and root crops (seed grass and field beans in System B2), respectively (15 January, 1976).

in the subsoil was very small and similar for all systems.

With respect to the distribution with depth, potassium showed the same tendencies (Fig. 21) as phosphate, although less pronounced because potassium is more mobile than phosphate.

5.3.2.3 After the second crop rotation (autumn 1979)

The pH-KCl was still very similar for all tillage systems; only in the top 10 cm of System B2 was a one-tenth of a unit lower value found. This was due to the presence of a mulch at the surface of the soil and a smaller supply of CaO because fertilizers were not mixed with the soil.

The amount of organic matter in the arable layer (Fig. 22) of Systems A and C was distributed fairly uniformly. System B1 and especially System B2 had a much larger amount of organic matter in the top 5 cm of the soil than Systems A and C. This difference decreased with depth, and below 15 cm depth differences between systems

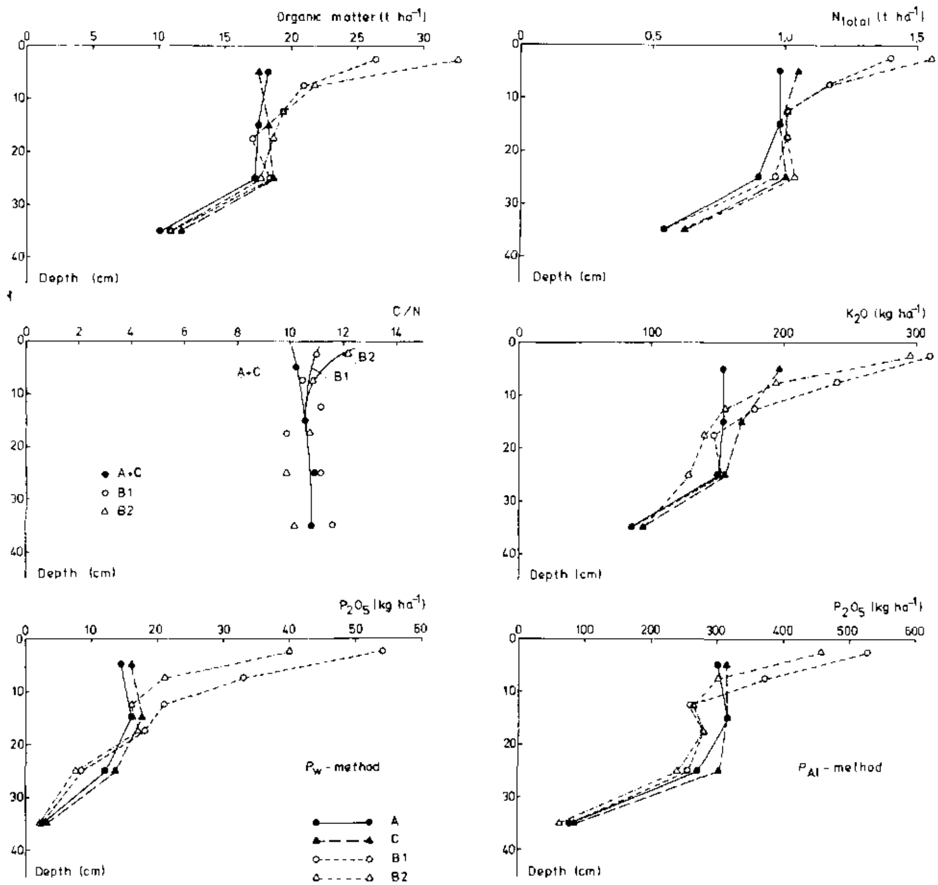


Fig. 22. Distribution with depth of the amount of organic matter, total nitrogen, phosphate and potassium in 5 cm layers, and C/N quotient at the end of the experiment (29 October 1979).

were not significant. In the top 30 cm the total amount of organic matter in Systems B1 and B2 was 14 and 20% higher, respectively, than in System A. System C had a 3% higher total amount than System A, which was entirely due to an increase in the 20 - 30 cm layer. At the end of the experiment the arable layer of Systems A and C contained nearly 7% more organic matter than at the start.

For N-total the same phenomena were observed as for organic matter content (Fig. 22). However, In Systems A and C the total amount in the 0 – 30 cm layer was 9 and 3% lower, respectively, than in 1971. System B1 scored 4% and System B2 9% higher than in 1971.

The C/N quotient of both tilled and untilled soil was small and, generally, differences between systems were not clear (Fig. 22). Only in the surface layer values of System B2 were somewhat higher than in tilled soil.

In Systems A and C the amount of water-soluble phosphate was rather uniformly distributed in the arable layer (Fig. 22). In the top 10 cm of Systems B1 and B2, phosphate had accumulated in the same way as organic matter. However here System B1 instead of B2 showed the largest accumulation, which is related to the heavier phosphate fertilization in the crop rotation with root crops. The amount of phosphate in the top 5 cm was about twice as high as in 1976. System B1 even showed accumulation in the 10 - 15 cm layer, probably because once in four years, when building up potato ridges, the soil was mixed to a depth of 8 - 10 cm. In the 20 - 30 cm layer, in both Systems B1 and B2 smaller values were obtained than in Systems A and C. In the top 40 cm of Systems B1 and B2 the total amount of phosphate was 63 and 24% higher, respectively, than in System A. System C had a 10% higher total amount than System A. In 1979 the amount in the top 30 cm of Systems A and C was 18% higher than in 1971 and 5% higher than in 1976.

When phosphate was determined by extraction with ammonium lactate (P-Al) the same general tendencies were found as with the P-water method, although there were some important differences (Fig. 22). In the top 30 cm the total amount of phosphate according to P-Al was in Systems A and C about 20 times, and in Systems B1 and B2 about 15 times, higher than according to P_w. In Systems A and C this ratio was fairly uniform with depth. However in Systems B1 and B2 this ratio increased from 10 and 11 in the 0 - 5 cm layer to 30 and 32 in the 20 - 30 cm layer, respectively. In the subsoil values are close to 30 in all systems. Therefore, in the top 5 cm of Systems B1 and B2 a less pronounced phosphate accumulation was found with the P-Al method than with the P_w method. Even below 10 cm, instead of below 20 cm with the P_w method, smaller values were found in the no-tillage plots than in Systems A and C. Differences in total amounts between systems (0 - 40 cm) therefore were also smaller: Systems B1 and C had, respectively, a 9% and 6% higher, and System B2 a 1% lower, total amount than System A.

For potassium the same tendencies were observed (Fig. 22) as for P_w, although somewhat less pronounced because potassium is much more mobile than phosphate. In the top 10 cm, also in System C, some accumulation was observed. In contrast to P_w, the amount of potassium in the lower part of the arable layer of System B1 was not smaller than in System A. Compared with System A the total amount in the top 40 cm of Systems B1 and B2 was 24 and 13% larger, respectively. System C had a 13% higher amount than System A, a tendency which was already present to some extent in 1976. However, in 1979 the total amount in the top 30 cm of System A was 18% smaller than in 1971.

5.4 Discussion

During the eight years of the experiment the amount of organic matter in the top 20 cm of tilled soil increased with about 0.5 t ha^{-1} $year^{-1}$. This may be explained by an increased organic matter supply as a result of including green manure crops in the crop rotation and leaving straw, stubbles and organic debris in the field. However, no-tillage with a crop rotation including root crops accumulated about 2.0 t ha^{-1} $year^{-1}$, and no-tillage without root crops even about 3.1 t ha^{-1} $year^{-1}$ organic matter. Especially the last situation, including grass green manure as well as seed grass, more or less resembled the conditions of arable land that is sown in for permanent grassland. In the Netherlands, in 1 - 10 years old grassland on sandy soil, an average increase in the amount of organic matter of 2.3 t ha^{-1} year^{-1} was found ('t Hart, 1950). During the first 5 years of two experiments on a clay soil the increase was even 4.2 t ha^{-1} year^{-1}. This larger accumulation was accounted for by the existence of a shallower sodlayer in clay than in sandy soil.

With no-tillage in a crop rotation without root crops, the organic matter in the mulch layer at the soil surface decomposes at a slower rate than in tilled soil, where the organic matter is mixed into the soil. A good contact between organic matter and a humid, well aerated, nicely crumbled soil, with a sufficiently high temperature, enhances microbial activity and, therefore, the decomposition. In contrast, when organic matter has been ploughed under as a layer, or is in contact with puddled soil, under wet soil conditions decomposition can be inhibited temporarily by insufficient aeration. With no-tillage the mulch was incorporated slowly and only superficially into the soil by the soil animals. (e.g. earthworms), sowing operations with a triple disc drill and field traffic. Moreover, compared with tilled soil, in untilled soil root growth was concentrated in the surface layer. In many microsites of the dense untilled soil, temporary anaerobiosis (see Chapters 8 and 9) and increased C/N quotient will have retarded the decomposition of this high concentration of organic matter.

With no-tillage the organic matter supply was somewhat less in a crop rotation that included root crops than without root crops. Moreover, in the crop rotation including root crops a shallow seedbed was prepared and once in four years the soil was even tilled to 8 – 10 cm depth for ridging potatoes. It is therefore understandable that accumulation of organic matter was less pronounced than with 'pure' no-tillage in a crop rotation without root crops.

The accumulation of organic matter was accompanied by immobilization of nitrogen and an increased C/N quotient. As a consequence, the amount of mineral nitrogen as found in January was smaller in untilled soil than in tilled soil, especially during the first year of the experiment. It is possible that differences in nitrogen availability between tillage systems disappeared during the growing season (Dowdell & Cannell, 1975). Nevertheless, during the first years of the experiment, for maximum yields untilled soil often needed a higher nitrogen fertilization than tilled soil. The accumulation of organic matter decreased with time and therefore differences in the amounts of mineral nitrogen between tillage systems gradually disappeared. After four years, no-tillage in a crop rotation including root crops released the same amount of mineral nitrogen as ploughed or cultivated soil. In a crop rotation without root crops this situation was reached at least two years later. Nevertheless, untilled soil performed better if more fresh nitrogen had been applied (Chapter 7). However, when comparing the response curves for fresh nitrogen application in the 1972 – 1975 and 1976 – 1979 periods, the impression may be gained that during the last four years of the experiment less extra nitrogen was needed. This is supported by the observation made at the end of the experiment, that in System B2 the accumulation of N-total was 66 kg ha^{-1} year^{-1}, which is about the same as found in permanent grassland (Hoogerkamp, 1973) and that C/N quotients were small and nearly similar in all systems. During the growing season, therefore, on tilled and untilled soil, availability of mineral nitrogen could have been similar. However, because at high soil water potentials on untilled soil many more microsites have an insufficient aeration, chances of denitrification are clearly higher.

Between years, large differences in the amount of soil mineral nitrogen were found. These may be caused by differences in mineralization or losses of nitrogen in the period between tillage and sampling. The losses of nitrogen, either by leaching or denitrification are influenced by the amount and distribution of precipitation. In the winter of 1976 the precipitation was very low, nitrogen losses were small and therefore, the amount of nitrogen found in January 1977 was large (114 kg ha^{-1}). After normal rainfall in the winters of 1975, 1977 and 1979, the amount of nitrogen was between 60 and 90 kg ha^{-1}. The small amount of nitrogen found in January 1979 (41 kg ha^{-1}) was caused by a wet period in December 1978.

It appeared that differences in the total amount of mineral nitrogen in the 0 - 100 cm layer were due mainly to differences found in the 60 - 100 cm layer. When rainfall in autumn and winter is small or evenly distributed, losses by denitrification are small and the total amount of mineral nitrogen large. A relatively great part of this mineral nitrogen was present in the 60 - 100 cm layer. Because nearly all nitrogen is released in the topsoil, this means that much mineral nitrogen was transported downwards. When rainfall in autumn and winter is large or unevenly distributed, this downward transport will be even greater. This depletes the topsoil to a larger extent and more mineral nitrogen will be lost by leaching to depths beyond 100 cm. As a consequence, the total amount found in the 0 - 100 cm layer was small. Nevertheless, a great part of this small amount was found in the topsoil instead of the subsoil, which points to increased denitrification in the subsoil. This is supported by the observation (Chapters 8 and 9) that even on this permeable and well-drained soil, during prolonged rainfall the ground-water table temporary rises to ploughpan depth.

The amount of mineral nitrogen as found in January in the soil profile was also influenced to some extent by the amount of mineral nitrogen left in the soil by the previous crop. At harvest of winter wheat and spring barley mineral nitrogen is usually nearly exhausted: only 10 - 20 kg ha^{-1} is left (Titulaer, 1978, 1980). After harvest the undersown grass green manure was fertilized with nitrogen at a rate of 50 kg ha^{-1}, but all this nitrogen was taken up by the grass before the main tillage was performed. Also sugar beet, due to the long growing season, left only a small amount of nitrogen, both in the topsoil and in the subsoil. Potatoes, however, left much more nitrogen in the subsoil because on this soil type root penetration into the subsoil is very limited (Boone et al., 1975).

Four years after the start of the experiment reliable cumulative nitrogen effects were not found. This is in accordance with the experience (van Ouwerkerk & Pot 1979) that at harvest only 10% of the nitrogen fertilizer applied to a particular crop is still present in the soil. Because differences in amount of nitrogen fertilizers applied were plus or minus 20% of the normal rate, this will result in differences of only - 2 and + 2% of the amount of soil mineral nitrogen found at the normal rate.

In untilled soil phosphate and also potassium accumulated in the surface layer. This could be expected because these elements, especially phosphate, are less mobile than nitrogen and because fertilizers and mulch were not, or only superficially, mixed into the soil. Differences between loose-soil husbandry and rational tillage in repartition of these elements within the topsoil could be explained by differences in tillage depth and degree of turning or mixing of the soil (van Ouwerkerk & Pot, 1979).

The amount of phosphate in the soil was measured by extraction with ammonium lactate (P-Al) or water (P_w). The ratio between the amounts found according to the former and the latter method was much smaller in the surface layer of untilled soil than in tilled soil. In the 20 – 30 cm layer the reverse was found, although the subsoil values were similar. With water the weakly absorbed, readily available phosphate is extracted, but with ammonium lactate part of the stronger absorbed phosphate is also determined. Therefore, it may be concluded that in untilled soil, and especially in the surface layer, phosphate was more readily available for the plant than in tilled soil. Decomposition of organic matter by micro-organisms is accompanied by acidification of the soil in the direct vicinity, which, in its turn, locally increases phosphate availability. When the soil is frequently mixed and displaced to greater depths, as was the case with loose-soil husbandry and rational tillage, these acid spots are diluted and neutralized. As a result in untilled soil the total amount of readily available phosphate was clearly higher than in tilled soil. Differences between tillage systems were much smaller when ammonium lactate was used, indicating that the total amount of phosphate was only slightly higher in untilled soil.

5.5 Conclusions

1. With no-tillage, especially in a crop rotation without root crops, organic matter accumulated in the surface layer. After eight years the total amount of organic matter in the topsoil was clearly higher in untilled than in tilled soil.

2. The accumulation of organic matter was accompanied by immobilization of nitrogen. At the beginning of the experiment, less nitrogen was available in untilled soil in January, but after one four-year crop rotation including root crops, nitrogen availability was equal to that in tilled soil. In a crop rotation without root crops this situation was reached at least two years later.

3. Four years after the start of the experiment significant cumulative effects of perennial nitrogen levels on the amount of mineral nitrogen in the soil profile were not found.

4. Between years, large differences in amount of soil mineral nitrogen determined in January occurred, which were related to differences in precipitation in the previous period. Even in a relatively dry winter a considerable amount of nitrogen was leached from the topsoil. In a relatively wet winter, losses by leaching and denitrification clearly increased.

5. Primarily due to a superficial rooting on this soil type, potatoes left much more nitrogen in the subsoil than sugar beet and cereals.

6. Eight years of no-tillage decreased the pH-KCl of the surface layer of this calcareous marine loam only to a minor degree.

7. Phosphate accumulated in the surface layer of untilled soil but at greater depths in the topsoil some depletion was observed. Total amounts in the topsoil were only slightly larger in untilled than in tilled soil. However, in untilled soil, especially in the surface layer, phosphate was more readily available to the plant than in tilled soil.

8. The accumulation of potassium in the topsoil of untilled soil was less pronounced than with phosphate, which can be accounted for by a larger mobility. Total amounts in the topsoil were somewhat larger in untilled than in regularly ploughed soil. When, in two out of four years, ploughing was replaced by fixed-tine cultivation, a slight accumulation was found in the surface layer and the total amount was slightly larger than in regularly ploughed soil.

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6 Rooth growth in relation to soil profile and tillage system

I. Ovaa & L.A.H. de Smet

6.1 Soil profile

The soil of the experimental field was sedimented in a saltish or brackish environment, influenced by the tide of the Nort Sea. The young embankements, among them the Westmaas Nieuwland Polder (Hoeksewaard), endiked in the 16th century, are considered part of the New land (Sediment of Dunkirk IIIb). These polders have the highest clay content along the oldest dikes and the lowest clay content along the youngest dikes. These differences in clay content are also found in the various parcels of the Experimental Husbandry Farm Westmaas. The parcel on which the experimental field was located is homogeneous and belongs to the most frequently occurring soils of the area. These are 'polder vague' soils, calcareous (de Bakker & Schelling, 1966) or Typic Fluvaquent, fine silty mixed (calcareous), mesic (Soil Survey Staff, 1975). The plough layer consists of loam, and the subsoil is a sandy loam (Table 35). On the Soil Map of the Netherlands, scale 1 : 50 000, the mapping unit of these soils is Mn25A (Institute for Soil Survey, 1967). The organic matter content is also typical for this area: about 2% or a little more in the topsoil; and about 1%, or a little less, in the subsoil.

Formerly the alluvial soils were drained by small ditches 15 – 20 m apart. Later on, to increase parcel size, the ditches were filled with soil material from the top layer and the parcels were tile-drained. Clear effects of these operations were found in the subsoil of the experimental field.

In the southwest of the Netherlands, many arable soils have a distinct compacted layer just below the ploughed layer (Stiboka, 1971). This layer, generally described as ploughpan, was found nearly everywhere in the experimental field at a depth of about 30 cm below the surface.

The subsoil shows a rather rapid decrease in clay content: the variation in depth at which soil with a low clay content is found is only small. This sandy loam subsoil is slightly stratified and it has a finely-channelled structure with mainly vertical pores. The diameter of these macro-pores, visible to the naked eye, is mainly between 100 and 1200 μm; only a small number has a larger pore diameter. Pores with a diameter $> 150 \mu$m, which can be considered as rootable, amount to about 4% of the total volume. Gley phenomena gradually increase with increasing depth. The totally reduced and not ripened horizon is to be found deeper than 150 cm below the soil surface.

The following profile description with approximate depth indications for a normally ploughed field is in accordance with the System of Soil Classification for the Netherlands (de Bakker & Schelling, 1966):

Table 35. Characteristics of the soil profile (0 - 100 cm).

Horizon	Depth (cm)	Org. matter (%, w/w)	Particle-size distribution of fraction, (%, w/w of fine earth)					CaCO3 (%, w/w)	pH (KCl)
			<2	2 - 16	16 - 50	50 - 105	>150 μm		
Ap1 + Ap2 Ap3	0 - 26 26 - 31	2.3	22	11	33	32	2	8.3	7.3
C21g	31 - 37	1.2	17	9	37	34	3	12.8	7.5
C22g	37 - 50	1.2	15	9	40	34	3	13.4	7.6
C23g C24g	50 - 90 >90	1.2	11	7	33	45	5	12.1	7.8

Ap1 + Ap2	0 - 26 cm	Dark grey (2.5Y4/2) loam; calcareous; moderately poor in organic matter; loose to firm structure; abrupt, smooth boundary.
Ap3	26 - 31 cm	Material similar to Ap1; has formerly been ploughed; compacted structure (ploughpan); abrupt, smooth boundary.
C21g	31 - 37 cm	Grey (2.5Y5/2) loam; calcareous; very poor in organic matter, has formerly not been ploughed; compacted structure with a few spots of rust (ploughpan); abrupt, smooth boundary.
C22g	37 - 50 cm	Grey (2.5Y5/1) sandy loam; calcareous; very poor in organic matter; spongy structure with channels, biopores and more sports of rust; gradual, smooth boundary.
C23g	50 - 90 cm	Grey (5Y5/1) sandy loam; calcareous; very poor in organic matter; spongy structure with channels, biopores and many spots of rust; gradual, smooth boundary.
C24g	>90 cm	Grey (5Y5/1) sandy loam; stratified with sandy layers; calcareous; very poor in organic matter; spongy structure with many spots of rust.

6.2 Methods

In 1977, 1978 and 1979 groundwater levels between the tile drains were measured weekly in duplicate and the daily precipitation was calculated for ten-day periods.

Characteristic soil horizons of Systems A, B1 and C were sampled by pressing 100 cm^3 cores horizontally into the walls of profile pits. The sampling, with five and three replicates in the topsoil and subsoil, respectively, was done in spring shortly after sowing or planting.

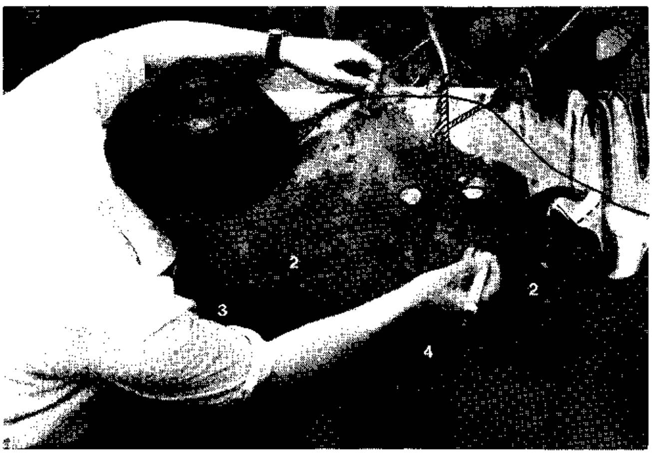
Penetration resistance of the soil profile was determined in spring, when soil moisture about equalled field capacity, with a penetrograph (van Soesbergen & Vos, 1972). A cone with a base of 1 cm^2 and a 60° angle was used. At each location the measurements were repeated five times. Values obtained below the tilled layer were corrected for adhesion of soil to the iron rod of the apparatus.

During various growth stages root systems were studied on profile walls of Systems A, B1 and C using the modified Reijmerink method (Reijmerink, 1964; Böhm, 1979). A pit was dug with a width of 80 cm at right angles to the direction of sowing, down to rooting depth. A smooth vertical wall was prepared by cutting directly through the middle of the plant (potatoes and sugar beet) or as close as possible to the stalks (cereals). A transparant plastic sheet was fixed on the wall and the soil horizons and boundaries of soil structure were sketched on the plastic sheet with a felt pen. After removal of the sheet the wall was prepared with a sharp-pointed knife to a horizontal depth of 2 – 3 mm to reveal as many roots as possible. The plastic sheet was again fixed on the profile wall and all visible roots were traced (Fig. 23). There were no replicates.

During the first year of the second crop rotation (1976) observations were made of potato and sugar beet roots on several horizontal planes. To this end the profile pit was excavated in layers and in the most representative part of each horizon or transition of horizons a smooth horizontal plane was prepared. Once the roots had been made visible, they were traced on plastic sheets.

After photographic reduction of the images on the plastic sheets, measurements were made of the surface areas of the various horizons and subhorizons. The number of roots per horizon was counted and the total for all horizons was calculated. From the surface areas and root numbers the root density was calculated.

The root systems were observed at the beginning and at the end of the growing season, and in the case of potatoes, sugar beet and spring barley in 1977 and/or 1978, also in mid-season. In 1976 no observations were made of winter wheat because System B1 was resown with spring wheat. If the dates of sowing or planting were not different among systems, root observations of a particular crop were made on a single day if possible. In 1977, however, sugar beet were sown one month later in System B1 than in Systems A and C. Therefore the root systems were observed on different dates but at approximately the same growth stage.



tuber ····· structural boundary 1 = loose
stalk —— boundary of horizon 2 = moderately dense
roots 3 = dense
4 = ploughpan

Fig. 23. Observation of the root system of potatoes on the wall of a profile pit. Soil structural boundaries, boundaries of soil horizons and visible roots are traced on a plastic sheet.

6.3 Results

6.3.1 Groundwater level and capillary zone

Due to the relatively high temperature and low precipitation during the growing season, 1976 was a very abnormal year. However, no data are available concerning the groundwater level of this particular year. In 1977, from May onwards, there was a considerable drop in the groundwater level (Fig. 24), which was due to a rather dry period from the middle of May to July. As a result of excess precipitation, this level rose about 12 cm during the two last ten-day periods of August. During the first part of 1978 there was a prolonged wet period, and only in the middle of July a period commenced when the evaporation was greater than the precipitation, which was clearly reflected in the groundwater level. In 1979, too, there were a few very wet periods in May and June. Thereafter, the groundwater level dropped and remained low for a considerable period as there was no great amount of precipitation until November.

In winter, the groundwater level generally varied between 60 and 90 cm depth. Once in a while, and then only for a short time, the groundwater level was shallower than 30 cm and thus in the topsoil. In spring, this level fell to 90 - 100 cm depth. The deepest groundwater level in summer was normally 180 - 190 cm below the surface.

The sandy loam subsoil has a large hydraulic conductivity. It was estimated that during dry periods the groundwater can supply more than 2 mm per day to the rooted zone. During the early summer of 1976 the capillary moisture front, clearly visible on the freshly cleaned slope of a dry ditch, was at a depth of 50 to 60 cm, whereas at that moment the groundwater level was deeper than 150 cm (Fig. 25). This boundary between wet and dry soil approximately corresponded with the transition of loam to sandy loam.

6.3.2 Pore space, water and air content

System A was ploughed to a depth of 25 cm each year, whereas System B1 in 3 out of 4 years was tilled for seedbed preparation to a depth of a few centimetres and only for potatoes to a depth of about 8 cm. At a pressure potential of -10 kPa (pF 2.0) the cultivated part of the topsoil of Systems A and C had a reasonable air content (Fig. 26). There was no real difference between loose-soil husbandry (System A) and rational tillage (System C). The air content in the non-tilled topsoil of System B1 hardly amounted to half of that in corresponding layers of Systems A and C. Moreover, in System B1, the air content increased only a few percent when a pressure potential of -50 kPa (pF 2.7) was reached. A low volumetric air content, especially during wet periods, possibly restricts the functioning of the roots due to oxygen deficiency (see Chapter 8 and 9). At a depth of about 30 cm, in all systems the volumetric air content strongly declined to a very small value, due to the presence of a ploughpan. In Systems A and C, this abrupt structural transition showed very clearly in the volumetric air content, because the topsoil was loose and the soil beneath the tilled layer was very firm. In System B1 such a structural boundary between loose and firm soil was found at a depth of 5 to 10 cm, the transition of the loose seedbed to the firm soil underneath.

The sandy loam subsoil with its rather-finely chanelled structure had an air content of only 6 - 7% (v/v) at a pressure potential of -10 kPa (pF 2.0). To reach this pressure

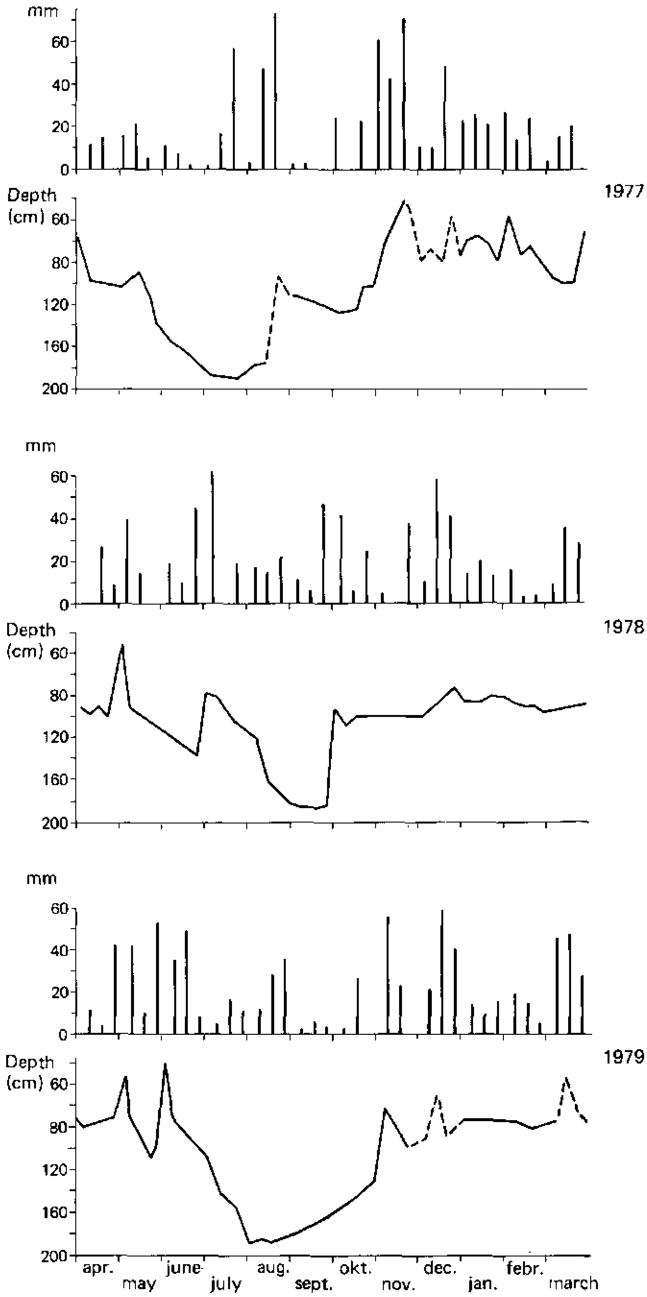


Fig. 24. Precipitation (P) and groundwater level (GWL) in ten-day periods in 1977, 1978 and 1979.

Fig. 25. Capillary moisture front on the freshly cleaned slope of a ditch (early summer 1976).

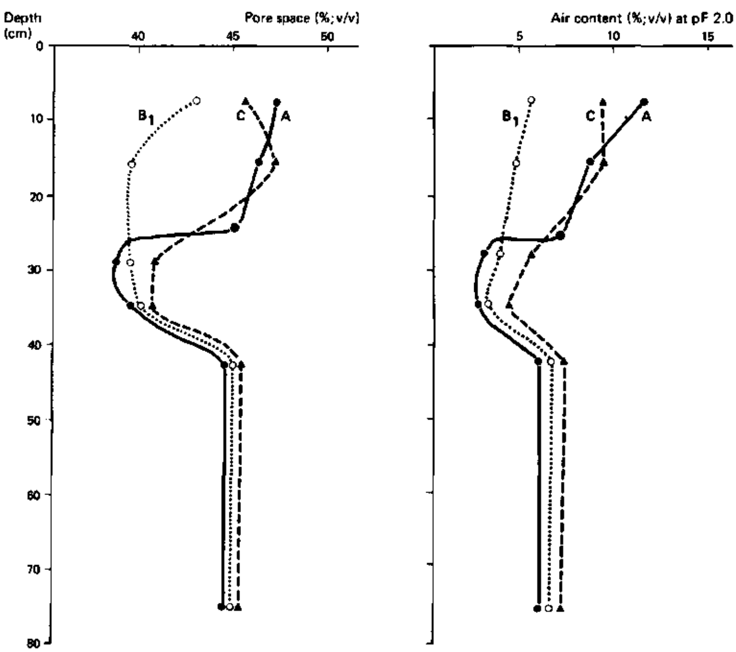


Fig. 26. Mean pore space and air content at a pressure potential of −10 kPa (pF 2.0).

potential a groundwater level of about 150 cm depth is required. Therefore, it is reasonable to expect that especially during wet periods the aeration in the subsoil will not be optimal, also because gas diffusion is hampered by the ploughpan (Boone et al., 1975; cf. Chapters 8 and 9).

6.3.3 Penetration resistance

Because differences between the diagrams obtained in the successive years were generally very small, only mean values are shown (Fig. 27). Penetration resistance of each of the various systems was different to a depth of about 30 cm. The high resistance in System B1 as compared with that of Systems A and C was rather striking. In all systems, between about 30 and 40 cm depth, values increased to 2.5 MPa and higher. These extremely high resistances, which were measured each year in all systems were caused by the ploughpan in both the Ap3 and C21g horizon. Below the ploughpan, in all systems, the penetration resistance decreased to about 2.0 MPa, which is still rather high.

The penetration resistance showed the greatest variation in the topsoil, which is influenced by tillage system, crop and, of course, soil moisture conditions. The loose structure of the tilled layer changed abruptly at a depth of about 30 cm into the strongly compacted ploughpan with a high penetration resistance. In System C, tillage depth was

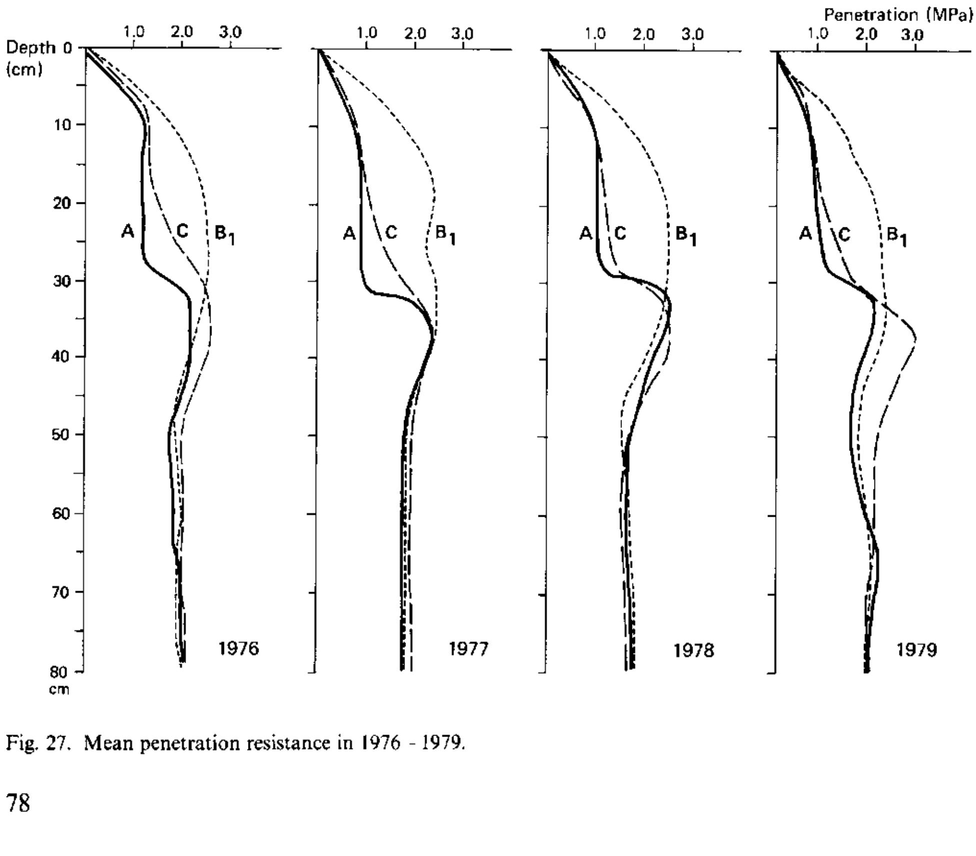


Fig. 27. Mean penetration resistance in 1976 - 1979.

Table 36. Mean penetration resistance (MPa) at depths of 5 and 10 cm (1976 - 1979).

Crop	5 cm			10 cm		
	A	B1	C	A	B1	C
Potatoes	0.3	0.7	0.4	0.7	1.1	0.7
Winter wheat	0.7	1.0	0.7	0.9	1.4	0.9
Sugar beet	0.7	1.2	0.7	1.2	1.7	1.2
Spring barley	0.5	0.9	0.5	1.0	1.7	0.8

generally shallower than in System A. After ploughing 25 cm for sugar beet, however, the resistance at a depth of 20 cm was more or less equal to that of System A, i.e. about 1.0 MPa. Three years later the resistance at that depth had increased to 1.5 – 2.0 MPa due to increased bulk density. The transition from the loosened toplayer to the compact ploughpan was therefore also more gradual than in System A. In System B1 under potatoes the soil was tilled to a depth of about 8 cm, which was reflected in a low penetration resistance at 5 and 10 cm depth (Table 36). In all systems the highest values were found in sugar beet. Winter wheat had somewhat higher values than spring barley. Between Systems A and C there were only slight differences. Due to seedbed preparation, as well as accumulation of organic matter and alternate drying and wetting cycles, the upper 5 - 10 cm of the soil was looser than the layer underneath.

6.3.4 Root observations

6.3.4.1 Depth of rooting

Rooting depth is affected by properties of the plant and the soil profile, such as a ploughpan or other compacted layers (Boone et al., 1978). The 1976 – 1979 average rooting depth is shown in Table 37. The lower boundary of the zone, which contained 90% of the total number of roots, was considered as the effective depth of rooting. In early summer, winter wheat had the greatest rooting depth. Vertical root growth of spring barley was somewhat slower but by the end of the growing season the roots had reached nearly the same depth as the winter wheat roots. Vertical root growth was slower under sugar beet, but ultimately a depth comparable to that of cereal roots was reached. Root development of potatoes was very different from that of cereals and sugar beet. Vertical growth was considerably slower and the depth of rooting was usually restricted to the bottom of the tilled layer. Potato roots were hardly capable of penetrating the ploughpan.

In Systems A and C in early summer the 1976 – 1979 average depth of the zones containing 90% and 100% of the total number of roots was similar (Table 37). Also at the end of the growing season differences between these systems were minimal. The root system of System B1 was 5 – 10 cm shallower than in both other systems. The vertical growth of the root system was impeded from the start and by the end of the growing season differences in effective rooting depth had not entirely disappeared. Nevertheless,

Table 37. Mean depth (cm) of the zones containing 90% and 100% of the total number of visible roots (1976 1979).

Crop	System	Early summer		Late summer	
		90%	100%	90%	100%
Potatoes	A	20	30	30	60
	B1	10	25	25	60
	C	15	30	30	60
Winter wheat	A	35	65	90	105
	B1	40	65	80	110
	C	40	70	90	110
Sugar beet	A	35	75	50	110
	B1	30	75	45	110
	C	40	75	50	110
Spring barley	A	35	60	80	100
	B1	40	60	70	100
	C	40	55	85	105

in all systems the greatest obstacles to deeper rooting appeared to be the ploughpan and the C horizon. At first the sugar beet root system was somewhat more superficial but by the end of the growing season it reached a depth comparable to that attained by cereal roots. Sugar beet root growth to depth in System B1 was somewhat slower than in both other systems and this difference in rooting depth persisted to the end of the growing season.

6.3.4.2 Total root number

Differences in total root number between years were significant and in general more pronounced in early summer than in late summer (Table 38). Even in late summer the number of roots varied between crops. Winter wheat had the greatest number of roots, followed by spring barley, potatoes and sugar beet, respectively. There appeared to be differences between tillage systems and years, but they were not very systematic. However, on average, the number of roots of potatoes, winter wheat and sugar beet was largest in 1976 and smallest in 1979. The number of spring barley roots did not differ much between years. The number of roots did not vary much between Systems A and C but, on average, significantly fewer roots were found in System B1. Therefore, it can be concluded that the looser structure of the tilled layer clearly promoted root growth.

6.3.4.3 Root density

Root density, generally declined with depth (Table 39). Compacted horizons such as the ploughpan, which have a high mechanical resistance and may diminish aeration, particularly at the beginning of the growing season, form an extra obstacle to root development. Therefore, in the subsoil the mean root density was much less than in the topsoil, especially with potatoes and sugar beet. The greatest differences in root density

Table 38. Total number of roots on a profile wall of a width of 70 cm and a depth of 100 cm.

Crop	Period	System	1976	1977	1978	1979	Average
Potatoes	June/July	A	1140	912	780	741	890
		B1	579	633	932	775	730
		C	800	604	864	812	770
	Aug.	A	1151	1294	1162	934	1140
		B1	1550	888	1050	946	1110
		C	1497	1170	1071	882	1520
Winter wheat	May	A	–	1032	522	723	760
		B1	–	540	659	545	580
		C	–	711	533	725	660
	June/July	A	–	1466	1659	1502	1540
		B1	–	1398	1400	1107	1300
		C	–	1468	1366	1273	1370
Sugar beet	June/July	A	485	336	566	514	480
		B1	840	260	709	455	570
		C	558	328	618	490	500
	Sept.	A	1315	949	774	815	970
		B1	1269	949	1084	739	830
		C	1035	848	873	778	880
Spring barley	June	A	496	932	945	905	820
		B1	791	511	997	804	780
		C	788	808	1097	898	900
	July	A	1111	1362	1252	1426	1290
		B1	791	1152	986	1332	1070
		C	1441	1276	1209	1417	1340

Table 39. Mean root density (number of roots per dm^2) in topsoil and subsoil and relative values at the end of the growing season (1976 – 1979).

Crop	System	Topsoil		Subsoil	
		number of roots (dm^{-2})	relative (%)	number of roots (dm^{-2})	relative (%)
Potatoes	A	45	95	3	5
	B1	34	95	2	5
	C	42	95	2	5
Winter wheat	A	40	80	12	20
	B1	42	75	13	25
	C	40	75	13	25
Sugar beet	A	32	90	4	10
	B1	45	85	8	15
	C	31	90	4	10
Spring barley	A	37	80	8	20
	B1	47	80	10	20
	C	43	80	10	20

between systems were found in the topsoil (Fig. 28). They were, however, not systematic. In the subsoil, differences were only small.

Within Systems A and C, root density was strongly correlated to the compactness of the soil in the Ap2 horizon (Table 40). Root density was clearly smaller within dense soil clods than within moderately loose soil. This phenomenon was observed in all crops. Although variability was quite high, the tendency is that root crops were more sensitive to a greater soil density than non-root crops.

Potatoes Very high root densities were found in the topsoil of all systems, whereas little or no rooting was found in the subsoil (Table 39). The greatest variation between years

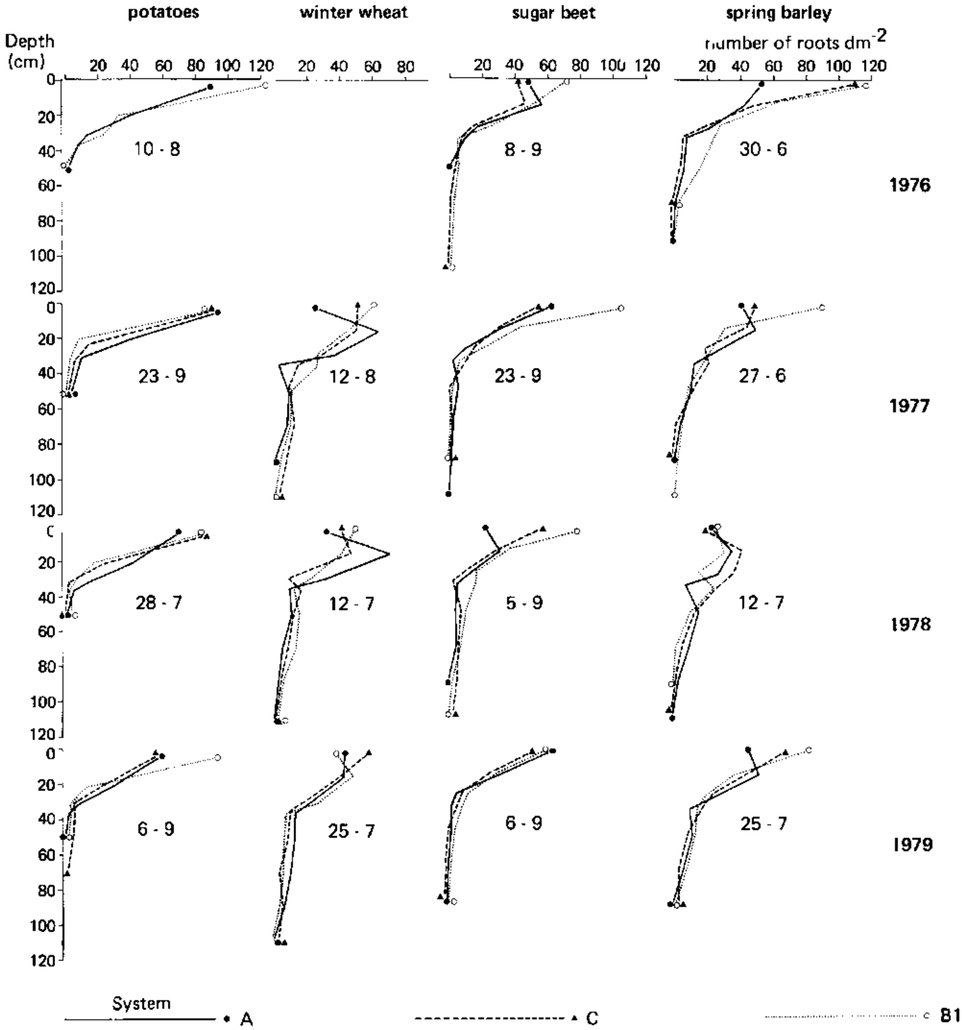


Fig. 28. Root density (number of roots dm^{-2}) on a vertical profile wall at about the end of the growing season.

Table 40. Root density in dense soil (clods) and in moderately-dense soil of the Ap2 horizon (10 - 25 cm) with a width of 70 cm (1977).

Crop	System	Dense soil		Moderately-dense soil		Quotient
		area (dm^2)	number of roots (dm^{-2}) = a	area (dm^2)	number of roots (dm^{-2}) = b	a/b
Potatoes	A	1.23	9.8	11.37	40.2	0.24
	C	2.20	6.8	9.00	21.9	0.31
Winter wheat	A	1.26	30.2	13.79	63.1	0.48
	C	5.21	36.7	8.79	54.4	0.67
Sugar beet	A	1.30	30.0	16.90	31.7	0.95
	C	3.20	5.6	12.90	40.5	0.14
Spring barley	A	2.00	34.5	14.80	50.9	0.68
	C	3.29	37.4	10.71	46.5	0.80

was found in System C, and the smallest in System B1 (Fig. 28). The lower boundary of the effective rooting zone, which contained 90% of the roots, therefore coincided with the upper boundary of the ploughpan in all systems. Only a few roots penetrated the ploughpan, most of them through vertical pores and channels.

The most intensive rooting in the topsoil was found in the potato ridge, where the mean root number per dm^2 at the end of the growing season was 80 for all systems (Table 41). There was a marked decrease to 15 per dm^2 in the compacted Ap2 of System B1, whereas System A still had about 40 and System C about 35 per dm^2 (Fig. 29). This reflects that the Ap2 was much looser in Systems A and C than in System B1. In all systems root numbers declined in the ploughpan.

Winter wheat The very loose seedbed (Ap1 horizon) of System A generally contained fewer roots than the somewhat more compacted Ap2 horizon beneath. There was no sign of this phenomenon in System B1, where the top layer often contained at least the same number of roots as the very dense horizon beneath. In all systems, root numbers declined

Table 41. Mean root density (number of roots per dm^2) in Ap1, Ap2, Ap3 and C21g horizons at the end of the growing season (1976 - 1979) for root crops.

Crop	System	Number of roots per dm^2			
		Ap1	Ap2	Ap3	C21g
Potatoes	A	80	40	10	5
	B1	80	15	5	4
	C	80	35	7	4
Sugar beet	A	45	30	10	4
	B1	80	40	20	8
	C	50	30	10	4

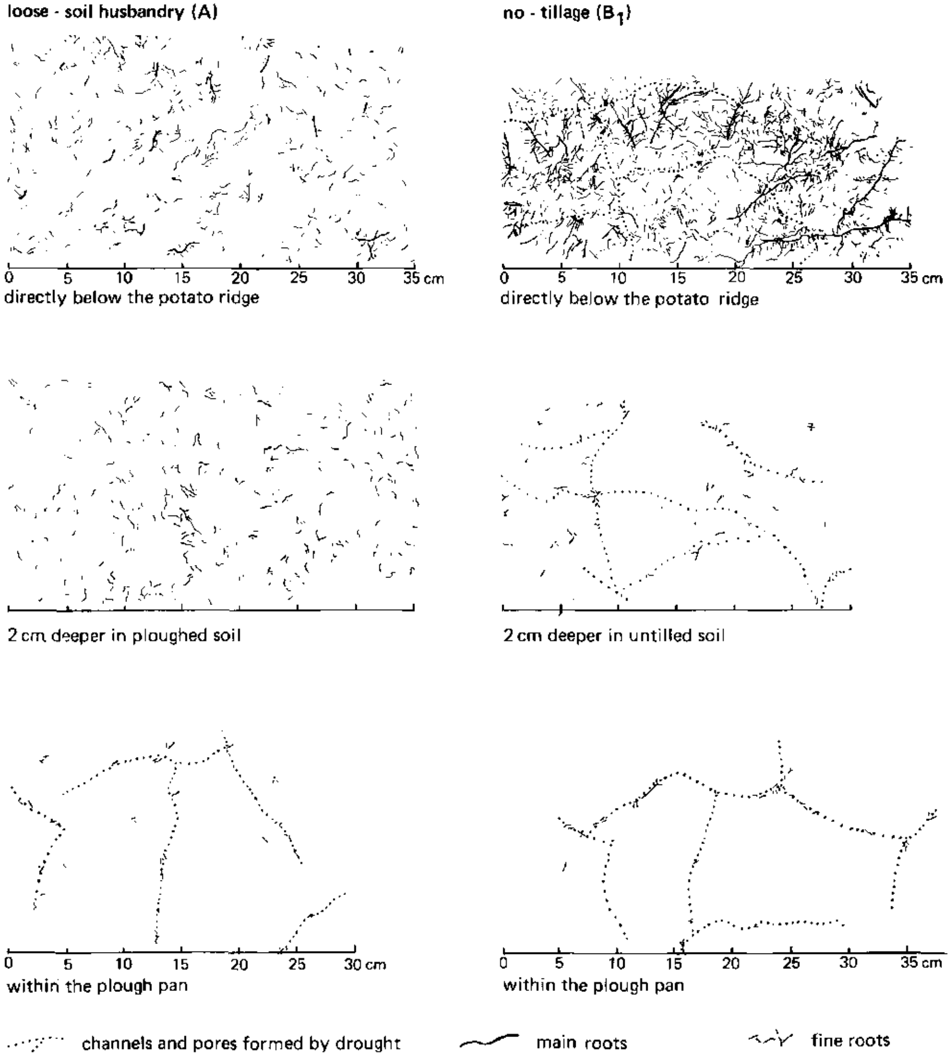


Fig. 29. Root development of potatoes at different distances below the ridge as observed on horizontal planes (1976).

in the Ap3 (ploughpan) and the horizons beneath. In some years the decrease in the C21g (ploughpan) was striking. The decrease deeper in the subsoil was fairly gradual in all systems. The topsoil (Ap1, Ap2 and Ap3) of System A contained 80% of the total number of roots. The equivalent figures for System B1 and System C are 75% and 75%, respectively (Table 39).

Sugar beet In comparison with cereals, the sugar beet crop had a less developed root system. Although the number of roots in the subsoil was clearly smaller than with cereals, maximum rooting depth was about the same. The topsoil (Ap1, Ap2 and Ap3) of all systems contained about 90% of the total number of roots in the profile (Table 39).

Mean root density in the Ap1 horizon of System B1 was more than 75 per dm^2 and of Systems A and C, 45 - 50 per dm^2 (Table 41). The variation in the Ap2 horizon was small: in System B1 40; System A somewhat more and System C somewhat less than 35 roots per dm^2. The relatively large number of roots in the Ap3 horizon of System B1, nearly 20 per dm^2 instead of 10 in the other systems, was striking. The C21g horizon also contained twice as many roots in System B1 (8 per dm^2) as in Systems A and C (4 per dm^2).

Spring barley The Ap1 horizon of System A had fewer roots than the Ap2 horizon. As a rule the toplayer of System B1 had most roots. The decrease in root numbers with depth was about the same as for winter wheat. In some years a relative low number was found in the ploughpan, as was most apparent in System A. The topsoil of all systems contained 80% of the total number (Table 39).

6.4 Discussion

Root growth depends on many factors, such as soil profile, groundwater level, precipitation, and soil tillage (Fig. 30). These factors are interdependent. For instance, drainage and the depth and thickness of the capillary zone are dependent on soil properties and groundwater level. The latter is influenced by precipitation. The effect of soil tillage operations, especially seedbed preparation in spring, depends on weather conditions. Weather conditions also affect soil aeration.

The greatest differences in number of roots were found in the topsoil. These differences were correlated with pore space and air content. Mean pore space and air content in

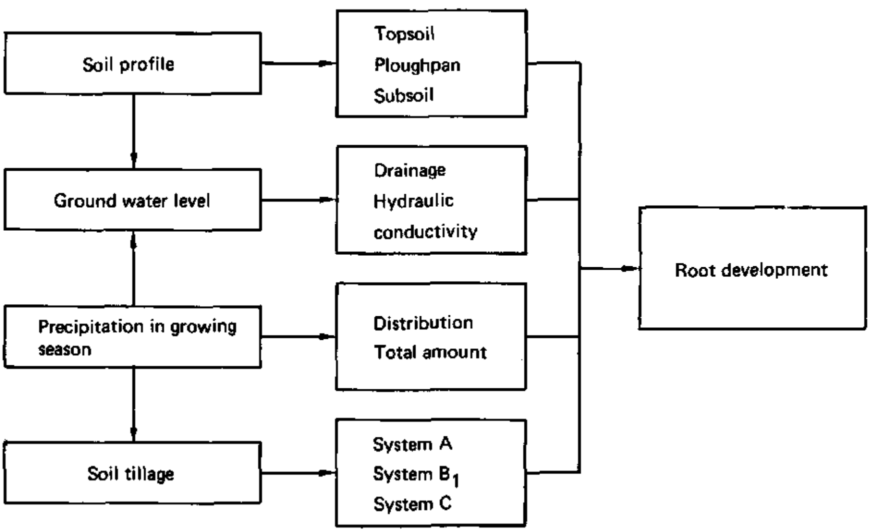


Fig. 30. Factors affecting root development.

the topsoil (Ap1, Ap2 and Ap3 horizons) were lowest in System B1 and highest in Systems A and C. The transition from the loosened top layer to the non-tilled layer was more gradual in System C than in System A. In System B1, it was only for the growth of potatoes that the tilled layer was loosened to a depth of about 8 cm. In the Ap1 horizon deviations of the mean values of root density were caused by differences in seedbed preparation for the different crops and by differences in climatological conditions with alternate drying and wetting cycles. The highest values were found in potatoes and the lowest in sugar beet. Winter wheat had somewhat lower values than spring barley. A low air content in the topsoil, especially during wet periods in the beginning of the growing season, is unfavourable for a good functioning of the roots. The general impression gained was that an air content $>10\%$ (v/v) is too low for maximum root development. In several years the greatest number of roots in the Ap1 horizon were found in System B1. In Systems A and C root density was also strongly correlated with the compactness of the soil clods in the Ap2 horizon (Table 40). Root density was clearly smaller within dense soil clods than within moderately loose soil. There was a tendency that root crops were more sensitive to a greater soil density than non-root crops.

The ploughpan in the Ap3 and C21g horizons was very compact in all systems, with a cone resistance of about 2.0 MPa or more, a pore space of about 40% (v/v), and an air content of about 5% (v/v) at pF 2.0. In Systems A and C the structural boundary between the loose soil of the tilled layer and the compacted soil of the ploughpan was abrupt. In System B1 a more gradual structural transition between loose and firm soil was found at a depth of 5 - 10 cm.

Roots hardly penetrate in compacted layers with an air content smaller than 10% (v/v) or in pores with a diameter <0.2 mm (Wiersum, 1975). Because ploughpans may have a sub-optimal aeration, a wet period in the beginning of the growing season is very unfavourable. In the course of the growing season air content increased as water content decreased and vertical fissures and channels were created through shrinkage. Roots of cereals and sugar beet were able to penetrate the ploughpan but in many cases root development of potatoes was restricted to the bottom of the tilled layer.

The relatively large number of roots in the ploughpan in System B1 was probably related to the gradual transition from the compacted Ap2 horizon to the ploughpan (Ap3 and C21g horizons). With an abrupt transition from a loose to a very compact soil, as in Systems A and C, the number of roots tends to decrease rapidly. This was also found for oats (Schuurman et al., 1974). Our observations confirm this for sugar beet and, to a smaller degree, potatoes. In all systems the subsoil (C22g horizon), with a penetration resistance of about 2.0 MPa, a pore space of about 45% (v/v), and an air content of less than 10% (v/v) at pF 2.0, was not ideal for root development. In the course of the growing season the air content in the subsoil increased, and the chances for rooting too. Roots of cereals and sugar beet, capable of penetrating the ploughpan, also penetrated the subsoil. At the end of the growing season, differences in rooting depth between systems were minimal and, except for potatoes, averaged 110 cm. The root system of potatoes with a maximum depth of 60 cm was more superficial. Below the ploughpan, to a depth of 60 cm, the root density was also very small. Only a few roots penetrated the ploughpan through vertical cracks and biopores (Ovaa & van Soesbergen, 1978). Therefore, in all systems the lower limit of the effective rooting zone, the part of the profile that contained 90% of all roots, coincided with the upper limit of the ploughpan.

6.5 Conclusions

1. Differences in number of roots between tillage systems and years were large but very unsystematic, especially for potatoes. Differences were much larger in the topsoil than in the ploughpan or the subsoil. The highest root densities in the topsoil were found for potatoes, followed by sugar beet, and the lowest for spring barley and winter wheat.

2. Rooting depth and root density in the subsoil were especially affected by properties of the ploughpan. By the end of the growing season, in all systems, roots of winter wheat, spring barley and sugar beet nearly reached the same depth (100 - 110 cm). Vertical root growth was somewhat slower in spring barley and sugar beet than in winter wheat. However potato roots were not capable of penetrating the ploughpan.

3. In all systems the ploughpan was very dense, with a penetration resistance of about 2.0 MPa or more, a pore space of about 40% (v/v) and an air content of about 5% (v/v) at pF 2.0. Such a ploughpan may diminish soil aeration and create an extra obstacle for root development. Roots of cereals and sugar beet were able to penetrate the ploughpan but potato roots could not.

4. The relatively large number of roots in the ploughpan of System B1 was related to the gradual transition from the dense Ap2 horizon to the ploughpan. An abrupt transition from loose to dense soil, as in Systems A and C, tended to rapidly decrease the number of roots with depth.

5. The subsoil with a penetration resistance of about 2.0 MPa, a pore space of about 45% (v/v), and an air content of $<$ 10% (v/v) was not ideal for root development. Roots of cereals and sugar beet, capable of penetrating the ploughpan, also penetrated the subsoil. In the subsoil the lowest root density was found with sugar beet and the highest with winter wheat.

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7 Crop response

C. van Ouwerkerk & L.M. Lumkes

7.1 Introduction

7.1.1 Length of the growing period

During the second crop rotation (1976 – 1979) the length of the growing period (Table 42) varied considerably less than during the first crop rotation (1972 – 1975).

For potatoes the length of the growing period was usually about 170 days, except in 1979 when, due to unfavourable weather conditions, planting had to be delayed for one month. In 1977 the growing period in System B1 was one month shorter due to late planting.

Generally, the length of the growing period for winter wheat was about 300 days; for spring barley it was about 140 days. In 1976, due to a dry and warm season, wheat was harvested about one month earlier than normal, which further reduced the growing

Table 42. Length of the growing period (days).

Year	Tillage system	Ware potatoes	Winter wheat	Sugar beet	Spring barley
1976	A	175	271	195	144
	C	175	271	195	143
	B1	174	157[b]	179[c]	143
	B2	.	155[b]	.	141
1977	A	161	308	173	158
	C	161	308	173	153
	B1	132[a]	308	141[d]	153
	B2	.	308	.	132[d]
1978	A	170	299	207	134
	C	174	298	207	134
	B1	167	298	207	134
	B2	.	313	.	134
1979	A	138[a]	319	215	131
	C	138[a]	316	215	131
	B1	138[a]	316	215	131
	B2	.	311	.	131

a. Planted one month later than normal.
b. Resown with spring wheat.
c. Sown three weeks later.
d. Sown one month later.

period in Systems B1 and B2, which had to be resown with spring wheat. In 1977 the growing period of spring barley in System B2 was about 3 weeks shorter due to late sowing.

For sugar beet the length of the growing period usually was about 200 days, except for System B1 in 1976 and 1977, due to sowing 3 weeks and 4 weeks later, respectively.

It may be concluded that in the second crop rotation the length of the growing period was usually about normal for all crops and that differences were mostly due to difficulties in seedbed preparation, which in its turn can be ascribed to unfavourable soil conditions.

7.1.2 Presentation of yield data

As explained in Chapter 1, on plots with the main crops potatoes, winter wheat, sugar beet and spring barley, crop response to nitrogen was tested in two ways:

1. with five annual nitrogen levels, ranging from 0 kg ha^{-1} to very high amounts, each year on one of the three repetitions (Table 3);
2. with three perennial nitrogen levels, ranging from 20% less (P–) to 20% more (P+) than the amount normally applied in agricultural practice (P), each year on all three repetitions (Table 4).

In the 1976 – 1979 period, contrary to the 1972 – 1975 period, yield data of the annual nitrogen levels were not always complete. Therefore, crop response to nitrogen could not be expressed relative to the mean yield at each nitrogen level. Consequently, yield data are now presented in the normal way: in graphs relating yield to annual nitrogen levels. However, because the annual nitrogen levels were non-replicated, the yield data sometimes had odd values. Therefore, in the graphs, the data points were not connected by straight lines but instead, to increase legibility, hand-smoothed curves were drawn.

The actual amount of nitrogen applied at perennial nitrogen levels differed between years and sometimes between the three repetitions of the experimental field, according to differences in plant-available nitrogen found in the soil profile in spring (Tables 4 and 31). Therefore, the yield data were, averaged for the three repetitions, presented in Tables with columns marked P–, P and P+. Besides, to facilitate comparison between years and between tillage systems, graphs were drawn relating average crop yield to the average nitrogen dose as actually applied in subsequent years of the second crop rotation.

7.2 Potatoes

7.2.1 Introduction

After harvesting the preceding crop (spring barley), 50 kg ha^{-1} of N was was applied to ensure a good development of the undersown English raygrass. However, also volunteer spring barley plants took advantage of the nitrogen dressing. Consequently, by the time of primary tillage in Systems A and C, a dense mixture of well developed grass and volunteer spring barley plants was present in all systems.

In System A this was no problem, because here ploughing to 25 cm depth always gave a good result: a coarsely crumbled soil with a level surface, and grass and volunteer spring barley plants completely covered. In System C, where tillage depth was restricted to 15 cm, ploughing was done with a seven-furrow skim plough, which has an attractive large working width of 2.00 m. However, the skim plough does not completely invert the soil and, therefore, grass and volunteer spring barley plants are not fully covered. To meet this drawback, grass and volunteer spring barley plants were killed off with paraquat applied at a rate of 3 l ha^{-1}. In System B1 no primary tillage was performed and, because in this system usually in places couch grass occurred, it was sprayed in autumn with glyphosate at a rate of 6 l ha^{-1}.

In System A, seedbed preparation, planting and ridging were combined in one pass. To obtain enough loose soil for building up potato ridges of sufficient volume, the soil was tilled with a rotating harrow as deep as possible and, if necessary, as intensive as possible (high rotational speed and low forward speed). The desirable working depth of 10 - 12 cm could only be achieved in 1976 and 1979. In 1977 and 1978 moisture content at 10 - 12 cm depth was too high for good workability and, therefore, working depth had to be restricted to 8 cm. Consequently, in these years potato ridges in System A were too small (Table 20).

In System C, in the dry spring of 1976 (Table 43) the autumn ploughed soil was nicely weathered and potatoes could be planted directly, without seedbed preparation. In 1977 - 1979 the soil was insufficiently weathered and an extensively working rotating harrow (low rational speed, high forward speed) was used for seedbed preparation. Then the soil was allowed to dry for a few hours and planting was performed in a separate pass. Later on the field was row-rotavated once and ridged up in the same pass to give the ridges their definitive shape and volume. This procedure usually gave a good external shape but within the ridges often a large plateau was created, the top of which was located at the bottom of the original seedbed (Fig. 11). In 1978 (very wet spring), the row-rotavator could only work superficially and, thus, only small ridges were obtained.

In System B1, seedbed preparation was always difficult as the non-tilled, mulch-covered soil remained wet for a much longer period of time than tilled soil, especially in the many wheel tracks made at spring barley harvest. Consequently, only in a very dry spring (1976) could System B1 be planted at the same time as Systems A and C. Spring 1977 was much wetter and, relative to Systems A and C (which were planted 17 days later than in 1976), planting in System B1 had to be postponed for one month (Table 43). Therefore in

Table 43. Precipitation (mm) during weeks I/VIII before and after planting of potatoes, 1976 - 1979.

Spring	Tillage system	Planting date	Before planting							After planting		
			I	II	III	IV	I/IV	V/VIII	I/VIII	I/IV	V/VIII	I/VIII
1976	A, C	8/4	2	8	5	19	34	13	47	4	29	33
	B1	9/4	2	5	8	19	34	8	42	4	29	33
1977	A, C	25/4	7	10	7	30	54	42	96	54	20	74
	B1	24/5	6	23	9	17	55	54	109	20	21	41
1978	A	22/4	3	28	0	8	39	65	104	63	27	90
	C	18/4	17	11	1	20	49	53	102	64	21	85
	B1	25/4	3	17	11	1	32	71	103	63	27	90
1979	A, C, B1	16/5	9	16	51	20	96	46	142	82	54	136

1978 and 1979, System B1 was harrowed some time before the expected date of seedbed preparation in Systems A and C to ensure that the top soil dried. Seedbed preparation in System B1 was performed with a full-width rotary harrow (3 m working width), which was working very intensively (pto: 1000 rpm; forward speed 1 km h^{-1}). In this way enough loose, finely crumbled soil was obtained, but the aggregates looked 'artificial' and, upon drying, they resembled cinders. Also in this system the soil was allowed to dry for a few hours before planting in a separate pass and, later on, the final shape and volume of the ridges was obtained by row-rotavating and ridging as in System C. However, in the non-tilled soil the row-rotavator does not penetrate as deeply and, therefore, the internal plateau was not as pronounced as in System C. Here too, only small ridges were obtained in 1978 (wet spring) (Table 20).

In all years the same cultivar ('Bintje E') was grown and in all systems the same number of seed potatoes (39 000 tubers, grade 35/45 mm) was planted, at a row distance of 75 cm and a distance in the row of 34 cm.

7.2.2 Crop development

Generally, crop development was best in System A. In System C, potatoes developed slower and, as a rule, System B1 lagged far behind. This correlates with the dying process, which was completed first in System A and then in System C, whereas in System B1 even at harvest some green haulm was still present. Crop development was particularly slow in the dry spring of 1976. Planting potatoes without seedbed preparation induced moisture shortage and emergence was delayed for one week. However, in 1978, when soil conditions at seedbed preparation were critical and potato ridges were small, crop development in System C was better than in System A.

7.2.3 Crop response to annual nitrogen levels

Gross tuber yield in System B1 was surprisingly not much less than in Systems A and C, and in the dry year 1976, when in Systems A and C gross yield level was very low (38 t ha^{-1}), it was even much higher (Fig. 31). Gross tuber yield was strongly influenced by nitrogen. In Systems A and C the nitrogen effect was similar but, as a rule, in System B1 the high maximum yields obtained in Systems A and C at high nitrogen rates were not equalled. The extremely high yield level reached in System B1 in 1976 must be regarded as a rare exception caused by extraordinary weather conditions. In all systems the optimum gross tuber yield usually was obtained at 240 kg ha^{-1} N, which practically coincides with the P level of the perennial nitrogen levels.

On average, saleable yield >40 mm was 14% less in System B1 than in Systems A and C, where saleable yields were similar (Table 44). The percentage net yield was about 78 in Systems A and C but in System B1 it was only 66. This was caused by a slightly higher percentage of tubers <40 mm (Table 45) but especially by a much higher percentage of cullings (green and misshapen tubers). In System B1, the percentage of cullings was particularly high in 1977, which was due to planting one month later than in Systems A and C. In 1976, probably due to planting without seedbed preparation, which delayed crop development, the percentage of cullings was much higher in System C than in System A. In 1978, when the gross yield level was high, the percentage of cullings was

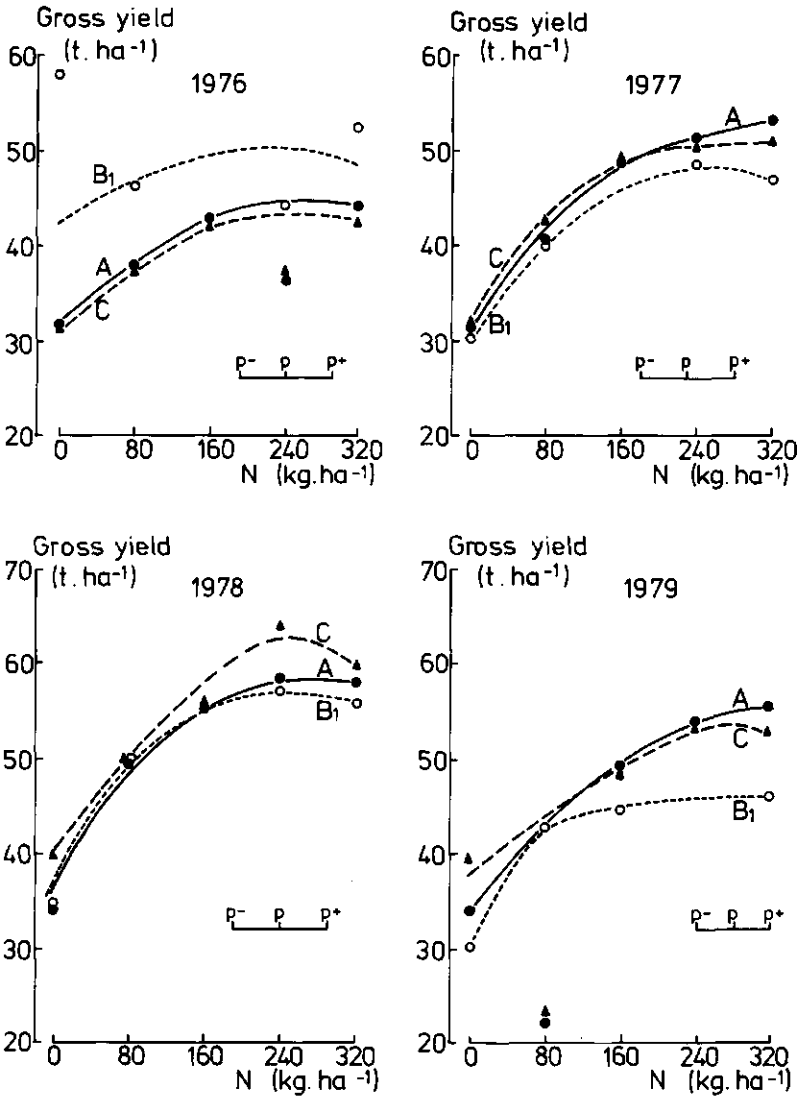


Fig. 31. Gross tuber yield of potatoes at five nitrogen levels in separate years in tillage systems A, B1 and C.

also high in both Systems A and C.

On average, the effect of nitrogen on saleable yield (Table 46) was slightly smaller in System C than in System A (48 and 59 kg of potatoes/kg of N), but in System B1 it was much less (39 kg of potatoes/kg of N). Especially at the higher nitrogen levels (which are normally applied in agricultural practice), System B1 lagged far behind. Probably root development in System B1 is then insufficient to make full use of the available nitrogen.

The grading of the tubers was strongly correlated with the yield level (Fig. 32). Usually the relationship between grading and gross tuber yield was about the same for all ha⁻¹ for Systems A, B1 and C, respectively. It is interesting to note that in all systems, relative to the normal nitrogen rate (P), the magnitude of the negative effect of 20% less nitrogen (P–) and of the positive effect of 20% more nitrogen (P+) was similar.

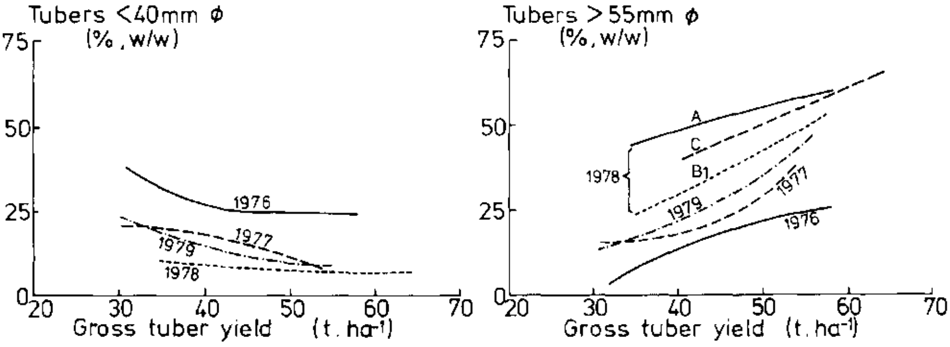


Fig. 32. Relationship between grading and gross tuber yield of potatoes in separate years.

Table 48. Clods and loose soil 'harvested' (t ha⁻¹), average of five annual nitrogen levels.

Year	A	C	B1
1976	1.9	2.4	2.2
1977	7.1	3.2	1.0
1978	1.2	7.1	1.3
1979	5.9	14.6	15.5
Mean	4.2	6.8	5.0
Rel.[a] (%, w/w)	9	15	11

a. Relative to gross tuber yield.

Table 49. 1976 – 1979 average net tuber yield of potatoes in the grade >40 mm at three perennial nitrogen levels.

System	Yield relative to mean at nitrogen level (%)			Mean yield[a]		Yield relative to System C (%)
	P–	P	P+	t ha⁻¹	rel. (%)	
A	95	100	106	39.6	103	95
B1	95	100	105	33.8	88	81
C	96	101	103	41.6	109	100
Mean	95	100	105	38.3	100	.

a. When 1977 is ruled out (System B1 planted one month later), mean yields amount to 38.4 (A), 36.1 (B1) and 41.0 (C) t ha⁻¹.

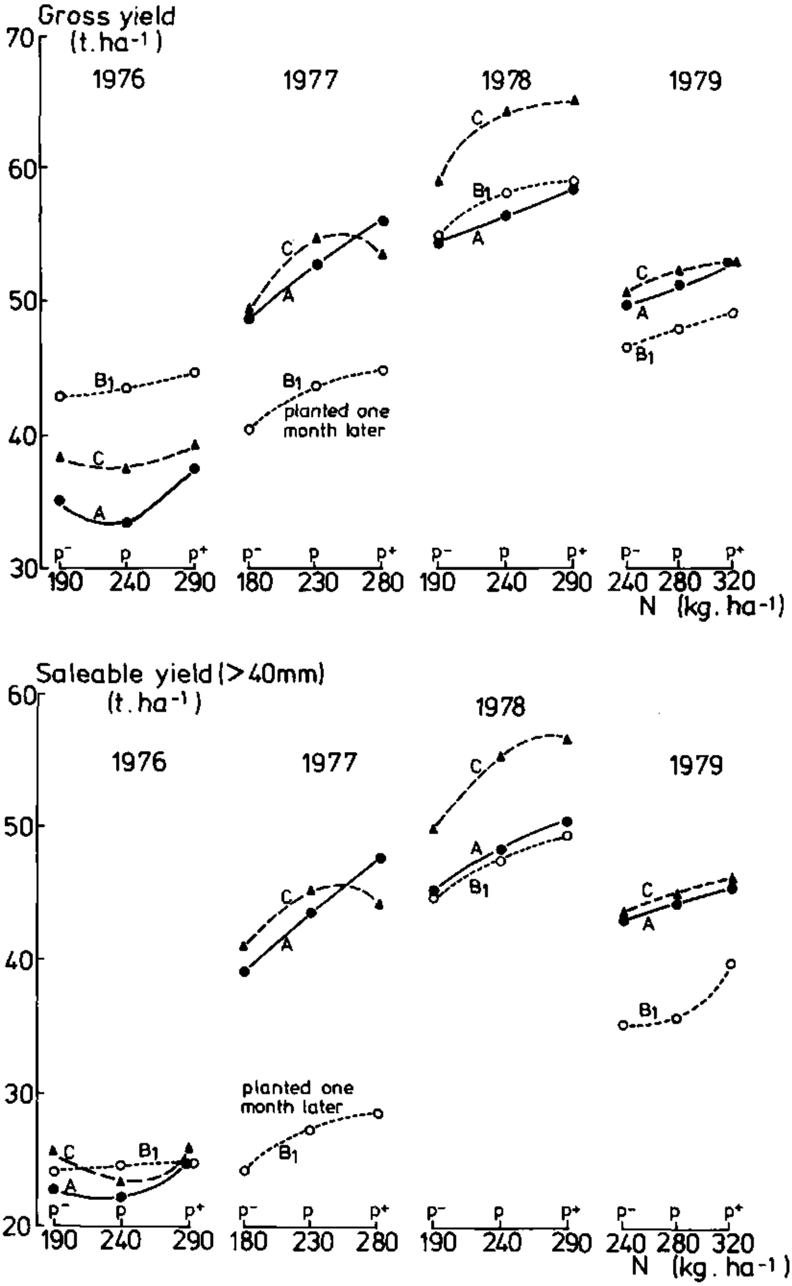


Fig. 33. Gross tuber yield and saleable yield (>40 mm) of potatoes at perennial nitrogen levels P –, P and P +, with indication of the fresh nitrogen dressings applied in separate years.

Table 50. Net tuber yield of potatoes, in the grade > 40 mm at three perennial nitrogen levels.

Year	System	Yield relative to mean at nitrogen level (%)			Mean yield		Yield relative to System C (%)
		P−	P	P+	t ha^{-1}	rel. (%)	
1976	A	98	95	107	23.3	96	94
	B1	98	100	101	24.6	101	99
	C	103	93	104	24.9	102	100
	Mean	100	96	104	24.3	100	.
1977	A	90	100	110	43.4	115	100
	B1	91	102	107	26.6[a]	70[a]	61[a]
	C	94	104	102	43.3	115	100
	Mean	92	102	106	37.8	100	.
1978	A	94	101	105	47.8	97	89
	B1	95	101	105	47.0	95	87
	C	93	102	105	53.7	108	100
	Mean	94	101	105	49.5	100	.
1979	A	97	100	103	44.1	106	99
	B1	95	97	108	36.8	88	83
	C	97	100	102	44.5	106	100
	Mean	96	99	104	41.8	100	.

a. Planted one month later.

The yields obtained with annual and perennial nitrogen levels were about the same, except for 1976 when annual nitrogen levels yielded much higher. Probably this was caused by the fact that yield determinations were always made with a two-row loading potato digger, except for 1976 when annual nitrogen levels were harvested by hand.

The continuing increase in yield at perennial nitrogen levels > P (Fig. 33) contrasts with the annual nitrogen levels where at 240 kg ha^{-1} N (≈P) the optimum yield was reached (Fig. 31). In all probability, however, the difference in yield at 320 kg ha^{-1} N (≈P+) between the non-replicated annual nitrogen levels and the triplicated perennial nitrogen levels are not statistically significant. Therefore, a conclusion about the possible cumulative effect of perennial nitrogen levels cannot be drawn.

7.3 Winter wheat

7.3.1 Introduction

After potato harvest, in Systems A, C and B1 the field was levelled by shallow working (5 - 7 cm) with a spring-tine cultivator in a transverse direction. In System B2 the seed grass stubble was killed off with glyphosate applied at a rate of 6 l ha^{-1} and burnt.

In System A ploughing to 25 cm depth was combined with drilling (drill at the side of the tractor). Usually ploughing produced a very cloddy soil, but the hoe that was attached to the drill crumbled the clods sufficiently to cover the seed. In System C, fixed-tine cultivation to 15 cm depth was combined with drilling (bridge-link). The fixed-tine cultivator brought a lot of coarse clods to the surface, where they were mixed with the loose, finely crumbled soil left behind after potato harvest. The seed environment thus was much finer than in System A (Table 27) but coarse enough to prevent serious slaking of the winter wheat fields. In System B1 the same combination of fixed-tine cultivator and drill was used as in System C, but here the working depth was minimal (about 6 cm). Consequently, much fewer coarse clods were mixed into the toplayer and, thus, the seedbed consisted mainly of finely crumbled, loose soil which easily slaked under the impact of autumn and winter rain storms. In System B2 no primary tillage was performed and drilling was done with the triple-disc drill which usually went smoothly. However, conditions were not always optimal for direct-drilling. In the autumn of 1976 the soil was moist and adhered to the discs and the seed slits were smeared. In contrast, in the autumn of 1977 the soil was so dry and hard that the discs could only produce a minimal slit and the seed could hardly be covered.

In 1976 and 1977, the cultivar Manella was used; in 1978 and 1979 the new, potentially higher yielding cultivar Arminda was introduced. In principle, the seed rate in Systems A, C and B1 was the same, but in System A, after disappointing results in 1977, about 9% and about 19% more seed was used in 1978 and 1979, respectively. In System B2, more seed was always used than in System B1 - on average 13% more (Table 51).

7.3.2 Crop development

In System A, the seedbed was never seriously sealed under the impact of rain and severe slaking did not occur (Chapter 4). However, in the dry autumn of 1976, conditions for emergence in the dry, cloddy seedbed, in which sowing depth probably was very irregular, were unfavourable and, thus, plant density in spring 1977 was sparse (Table 51). In System C, under the impact of rain, the seedbed usually capped and slaking occurred locally. In 1978 (after 130 mm of rain in the first four weeks after sowing (Table 52), this had a pronounced negative effect on plant density (Table 51).

In System B1, slaking occurred on a much larger scale and in spring 1976, after a wet November (110 mm) and an extremely wet January (91 mm), slaked parts were so large, especially in dips, that the field had to be resown with spring wheat. Also in spring 1979, after 112 mm of rain in December and 125 mm in January, large-scale slaking occurred and plant density was very low.

In System B2, burning of the seed grass stubble induced locally slaking, in 1976 so seriously that the field had to be resown with spring wheat. However, in 1979 slaking was much less than in System B1. In the autumn of 1977 insufficient covering of the seed allowed birds to do much damage. Moreover, during winter, so many seedlings suffocated in dips and ruts that in spring 1978 the field also had to be additionally sown with spring wheat.

As a rule, plant density in Systems A and C was of the same order of magnitude (Table 51). However, due to the coarser seedbed, the number of plants relative to the seed rate usually was lower in System A than in System C (on average 14.3 and 15.6 plants per gram of seed, respectively). In 1977 and 1979 plant density in System B2 was higher than in System B1. However, from the about equal number of plants per gram of seed it is apparent that this was caused by the substantially higher seed rate in System B2. Even in these years in Systems B1 and B2, the number of plants per gram of seed and, thus, plant

Table 51. Seed rate, plant density and plants per gram of seed of winter wheat.

		A	C	B1	B2
Seed rate (kg ha^{-1})	1976	140	140	150[a]	150[a]
	1977	140	140	140	150
	1978	153	140	140	164
	1979	155	130	130	155
Plants per m^2	1976	213	227	251[a]	200[a]
	1977	184	237	200	222
	1978	212	190	190	121[b]
	1979	231	202	136	182
Plants per gram of seed	1976	15.2	16.2	16.7[a]	13.3[a]
	1977	13.1	17.0	14.3	14.8
	1978	13.9	13.6	13.6	7.4[b]
	1979	14.9	15.5	10.5	11.7

a. Spring wheat (cv. Melchior; 150 kg ha^{-1}). Initially 140 kg ha^{-1} (B1) and 155 kg ha^{-1} (B2) winter wheat (cv. Manella) were sown.
b. Afterwards additionally sown with spring wheat (cv. Adonis; 100 kg ha^{-1}).

density, was much lower than in System C. Only in 1978 was the number of plants per gram of seed and, thus, plant density, the same in Systems B1 and C.

In 1976, resowing in Systems B1 and B2 took place after the killing of the remaining winter wheat plants and newly developed cleavers (*Galium aparine* L.) with 2.5 l ha^{-1} paraquat + 2.5 l ha^{-1} diquat. In System B1 the top layer was dry and nicely weathered by night frosts and, thus, working twice with a spring-tine cultivator resulted in a nicely crumbled seedbed in which spring wheat could be sown with a normal drill. However in System B2, the soil was superficially frozen, so the discs of the triple-disc drill could not penetrate deep enough, with the result that the seed was insufficiently covered. This

Table 52. Precipitation (mm) during weeks I and II before, and weeks I/VIII after sowing winter wheat, 1975 - 1978.

Autumn	Tillage system	Sowing date	Before sowing		After sowing						
			I	II	I	II	III	IV	I/IV	V/VIII	I/VIII
1975	A, B1, C	31/10	0	0	12	2	40	30	84	52	136
	B2	3/11	6	0	8	26	17	52	103	34	137
1976	A, C, B1, B2	27/10	8	7	2	5	17	13	37	92	129
1977	A, C, B1	25/10	24	0	3	39	34	59	135	64	199
	B2	21/10	0	3	24	27	35	39	125	95	220
1978	A	16/10	1	–[a]	18	14	4	1	37	57	94
	C, B1	19/10	8	–[a]	25	0	4	1	30	76	106
	B2	24/10	15	3	14	4	1	2	21	109	130

a. Potato harvest 9/10/78.

allowed so much damage by birds that plant density in System B2 was 20% less than in System B1.

In 1976 and 1977 the stand of the crop in System A was slightly irregular and sparse, but in 1978 and 1979, due to using more seed, a good, dense crop was obtained, as in System C. Crop development in Systems A and C was always satisfactory. However, in System B1 and especially in System B2 crop development was slower and more irregular.

7.3.3 Crop response to annual nitrogen levels

In the dry growing season of 1976, on average (all nitrogen levels included) the highest yield (6.6 t ha^{-1}) was obtained in System C. System A yielded on average about 6% less (6.2 t ha^{-1}), which may be ascribed to the 6% lower plant density (Table 51). In System B1, spring wheat yield was on average 5.9 t ha^{-1}, which is about 10% less than the yield of winter wheat in System C; this difference may be considered a normal difference between spring wheat and winter wheat yields. System B2 performed relatively well: in spite of an about 20% lower plant density (Table 51), the average yield of spring wheat was only about 14% less than in System B1.

Nitrogen had a pronounced effect on yield (Fig. 34). It was about the same for Systems A, C and B1 and the maximum yield was obtained at a nitrogen level of 120 kg ha^{-1}. In System B2, even at 160 kg ha^{-1} the maximum yield was not reached.

In 1977 the weather was much more variable than in 1976: April was very wet, June very dry and August extremely wet. Consequently, the yield level was about 30% lower than in 1976 (Fig. 35). Although yield data for nitrogen levels of 80 kg ha^{-1} are missing, it is clear that, with the exception of the highest nitrogen level (160 kg ha^{-1}), System C yielded highest. In System A, yield was about 10% less, and in System B1 it was in an intermediate position. Probably these differences are related to the differences in plant density (C: 237; A: 184; B1: 200 plants per m^2). In spite of a satisfactory plant density (222 plants per m^2), in System B2 without nitrogen application yield was much lower, but at higher nitrogen levels yields were about the same as in the other systems. At lower nitrogen levels, in Systems A, C and B1, nitrogen response was only small. At nitrogen levels of 160 kg ha^{-1} the yield in Systems C, B1 and B2 decreased sharply, but in System A it remained about the same as at levels of 120 kg ha^{-1} and, thus, was clearly higher than in System C.

In 1978 the weather conditions during the growing season were about normal and in Systems A and C, too, the yield level was about normal (as in 1976). In System B1 grain yield was about 10% higher than the yield of spring wheat in 1976, so for this system the yield level was also about normal. Yields in Systems A, C and B1 were similar, except at 160 kg ha^{-1} N, where System A yielded clearly higher than System C. In System B2 the mixed crop of winter wheat and spring wheat developed reasonably well but, due to bird damage, the stand was very irregular. Therefore, yield was lowest here, except at 160 kg ha^{-1}.

With the exception of July, the 1979 growing season was wet and cool, and, therefore, initially the wheat crop developed slowly and matured very gradually. The yield level in 1979 was highest and crop response to nitrogen was more pronounced than in any other year of the second crop rotation. Yield data were incomplete (Fig. 34), but it is clear that at nitrogen levels $>$ 120 kg ha^{-1}, System A yielded more than System C. Despite a very

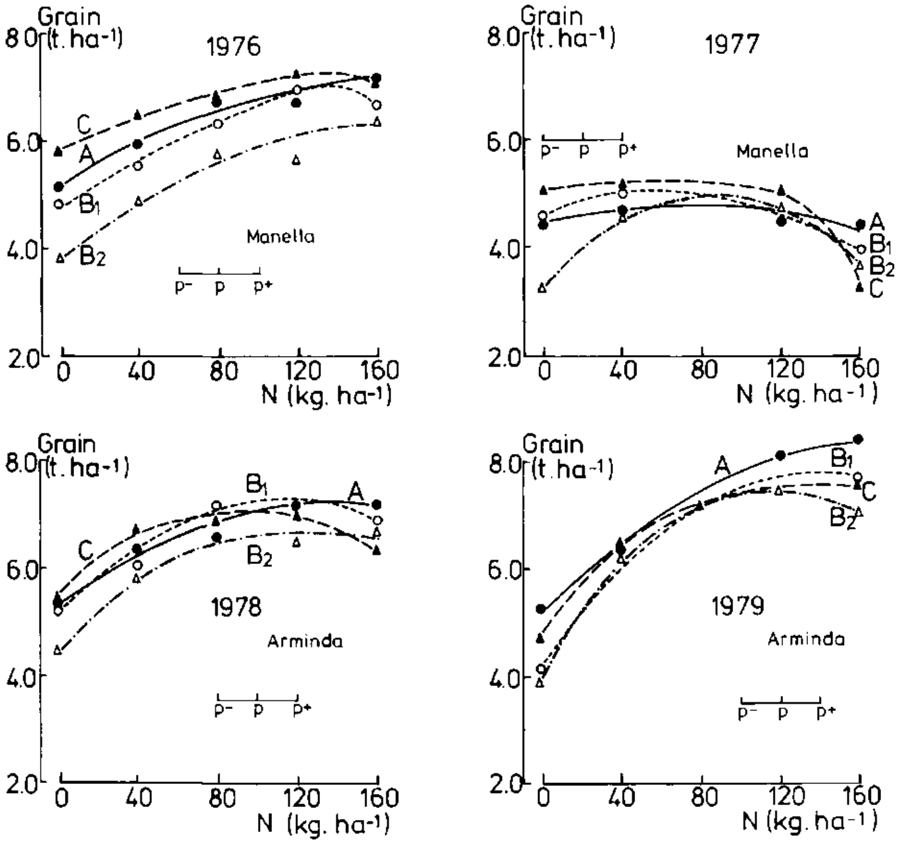


Fig. 34. Grain yield of winter wheat at five nitrogen levels in separate years.

low plant density (Table 51), yields in Systems B1 and B2 were about the same, except at 160 kg ha^{-1} N, where grain yield was clearly higher in System B1. At zero nitrogen levels Systems B1 and B2 had clearly lower yields than Systems A and C, but at higher nitrogen levels yields in Systems B1 and C were similar.

7.3.4 Crop response to perennial nitrogen levels

Yield results obtained with the perennial nitrogen levels are presented in Fig. 35, which shows that the yield level varied very much between years. However, this is only partly due to the variation in the rate of fresh nitrogen application. At comparable fresh nitrogen dressings yield levels were about the same as with the annual nitrogen levels (Fig. 34). Thus, the low yield level in 1977 must be ascribed to unfavourable weather conditions rather than to insufficient nitrogen. Contrary to the first crop rotation, nitrogen now nearly always had a clear positive effect on yield.

Crop response to nitrogen is further analysed in Table 53. It appears that within any one year the differences in mean grain yield between Systems A and C were small (<5%),

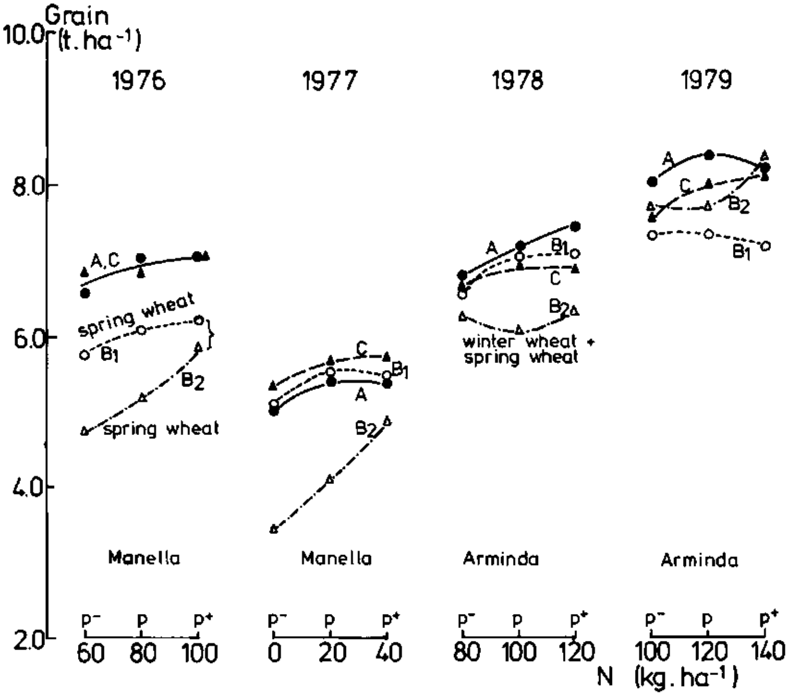


Fig. 35. Grain yield of winter wheat at perennial nitrogen levels P−, P and P+, with indication of the fresh nitrogen dressings applied in separate years.

and the relative influence of nitrogen levels was similar. Of course, in 1976 in Systems B1 and B2 spring wheat yielded much less than winter wheat in Systems A and C.

In 1977 and 1978 the yield level of winter wheat in System B1 was about the same as in Systems A and C, but in 1979, probably due to a very low plant density (Table 51) the yield level in System B1 was about 10% lower than in Systems A and C.

As a rule, crop response in System B1 to nitrogen was similar to Systems A and C, but in 1979 it was only small and slightly negative. In System B2, in 1976 and 1977, when yield level was very low, crop response to nitrogen was very strong. However, in 1978 and 1979 yield level was much higher and crop response to nitrogen was much smaller.

The average effect of nitrogen on grain yield in the four systems is difficult to compare because the number of years winter wheat was successfully grown differs. From the 1976 – 1979 average it appears (Table 54) that the difference in grain yield between Systems A and C was negligible and that the relative effect of nitrogen was similar: between grain yields at P− and P+ level the relative difference was 6% and 5% for Systems A and C, respectively. From the 1977 – 1979 average it appears that in System B1, mainly due to the low 1979 yield, the average yield level was 5% lower than in Systems A and C, and that the relative effect of nitrogen on grain yield was 4%. For System B2 a valid comparison with the other systems can only be made for the years 1977 and 1979. Then it appears that yield level was 10% lower than in Systems A and C and that the relative effect of nitrogen on grain yield was 16%. However, it is clear that the

Table 53. Grain yield of winter wheat at three perennial nitrogen levels.

	System	Yield relative to mean at nitrogen level			Mean yield		Yield relative to System C (%)
		P−	P	P+	t ha⁻¹	rel. (%)	
1976	A	96	102	102	6.9	110	100
	B1	96	101	103	6.0[a]	96	87
	B2	90	98	111	5.3[a]	84	76
	C	99	99	102	6.9	110	100
	Mean	95	100	104	6.3	100	.
1977	A	95	103	102	5.3	104	95
	B1	94	103	102	5.4	105	96
	B2	83	99	118	4.2	82	75
	C	96	102	103	5.6	109	100
	Mean	92	102	106	5.1	100	.
1978	A	95	101	104	7.2	106	105
	B1	96	102	103	6.9	102	101
	B2	100	97	102	6.2[b]	92	91
	C	98	101	101	6.8	100	100
	Mean	97	100	103	6.8	100	.
1979	A	97	102	100	8.2	105	104
	B1	100	101	99	7.3	93	92
	B2	97	97	105	7.9	101	100
	C	96	101	103	7.9	101	100
	Mean	98	100	102	7.8	100	.

a. Resown with spring wheat.
b. Additionally sown with spring wheat.

average value is too much biased by the extremely low 1977 figures to be truly representative for the nitrogen response of System B2.

As mentioned above, yield results of perennial and annual nitrogen levels differed only slightly and not systematically. Therefore, it may be concluded that the perennial nitrogen levels did not have demonstrable cumulative effects.

7.4 Sugar beet

7.4.1 Introduction

After winter wheat harvest, in Systems A and C the straw was chopped and spread, but in System B1 it was baled and removed to forestall problems when sowing sugar beet in spring. In all systems the undersown grass obtained a nitrogen dressing (50 kg ha^{-1}) to ensure a good development.

Because it is well known that sugar beet respond favourably to deeply loosened soil, ploughing depth in both Systems A and C was 25 cm. With this ploughing depth the undersown grass could be well turned under. In System B1 no primary tillage was

Table 54. Average grain yield of winter wheat at three perennial nitrogen levels.

Years averaged	System	Yield relative to mean at nitrogen level			Mean yield		Yield relative to System C (%)
		P–	P	P+	t ha^{-1}	rel. (%)	
1976 - 1979[a]	A	96	102	102	6.9	106	101
	B1	97	102	101	6.4	98	94
	B2	94	98	108	5.9	91	87
	C	97	101	102	6.8	105	100
	Mean	96	101	103	6.5	100	.
1977 - 1979[b]	A	96	102	102	6.9	105	102
	B1	97	102	101	6.5	99	96
	B2	95	98	107	6.1	93	90
	C	96	101	102	6.8	103	100
	Mean	96	101	103	6.6	100	.
1977 + 1979[c]	A	96	102	101	6.8	104	100
	B1	98	102	100	6.3	98	94
	B2	93	98	109	6.0	93	90
	C	96	101	103	6.7	104	100
	Mean	96	101	103	6.5	100	.

a. Valid comparison only between Systems A and C.
b. Valid comparison between Systems A, B1 and C.
c. Valid comparison between Systems A, B1, B2 and C.

performed and, therefore, some months after winter wheat harvest the grass was killed off with glyphosate applied at 6 l ha^{-1}.

At ploughing, the soil was crumbled much more strongly in System A than in System C, because in System A ploughing depth was always 25 cm and, thus, until that depth the soil was relatively loose, whereas in System C the 15 - 25 cm layer was relatively dense because in this system primary tillage for winter wheat and spring barley consisted of fixed-tine cultivation and for potatoes of ploughing, to a depth of only 15 cm. Moreover, in System A the field was levelled by harrowing in the same pass, which gave an additional crumbling of the topsoil.

In spring, the smoother, more strongly crumbled top layer in System A was always moister than in System C. Therefore, seedbed preparation with the powered harrow resulted in a coarser and less even seedbed than in System C, where the same implement was used.

In System A, seedbed preparation and sowing were combined in one pass. Consequently, prior to sowing the seedbed was not allowed to dry superficially, and, therefore, usually soil adhered to the seed coulters, which sometimes gave rise to clogging and, thus, to irregular sowing. In contrast, in System C the seedbed was allowed to dry for a few hours prior to sowing in a separate pass. Here sowing could be performed without any problem and, therefore, emergence was always much more regular in System C than in System A.

In System B1 the seedbed was prepared with a full-width rotary cultivator (3 m working width). However, because in non-tilled soil capillary rise of water is unimpeded, the top layer always remained wet for a much longer period of time than in Systems A and C, especially in places where some winter wheat straw still remained on the surface. Therefore, in System B1 sowing could only take place 14 days later (1976) or even one month later (1977) than in Systems A and C (Table 55). In 1978 and 1979, in System B1 the winter wheat stubble was harrowed some time before the expected date of seedbed preparation in Systems A and C. As a result, in System B1 the topsoil dried to the extent that, in all three systems, seedbed preparation and sowing could be performed on the same date. In System B1 the seedbed was always fine enough, but, as a consequence of the uneven surface (dips and ruts) and the shallow working depth of the full-width rotavator, seedbed depth was very variable (1 – 4 cm). In System B1 the seedbed had insufficient contact with the dense layer underneath the seedbed and, therefore, to prevent drying out, immediately after sowing the field was rolled with the Cambridge roller.

7.4.2 Crop development

In all systems a satisfactory plant density was obtained, even when in 1977 in Systems A and C drilling to a stand was introduced (Table 56). Precautionary, in System B1 the distance in the row was kept smaller (1977, 1979) to much smaller (1978) than in Systems A and C. In retrospect this was unnecessary because emergence in System B1 was at least as quick and regular as in System C. It is noticeable that, as a rule, in all systems relative emergence was not high (about 55% of the number of seeds sown). In 1976 in all systems, and in 1977 – 1979 only in System B1, the sugar beet were singled to a stand of 75 000 – 80 000 plants per hectare.

7.4.3 Crop response to annual nitrogen levels

In the dry year 1976, crop development in Systems A and C was good and in System B1, probably due to a better capillary transport of water, the sugar beet caught up completely after being sown 14 days later than in Systems A and C. Consequently, sugar yield in Systems A, C and B1 was similar (Fig. 36). In all systems nitrogen had a pronounced effect on sugar yield but only in System A an optimum was reached (at 180 kg ha^{-1}).

In 1977 weather conditions during the growing season were much less favourable than in 1976, and crop development was poor. Consequently, although sugar content was higher (Fig. 37), the sugar yield level was much lower than in 1976 (Fig. 36). In System A, due to a very irregular stand of the crop, sugar yield was much less than in System C. In System B1, due to sowing one month later than in Systems A and C, root yield, sugar content and sugar yield lagged far behind. In all systems, crop response to nitrogen was much less pronounced than in 1976.

In 1978 weather conditions were again favourable for sugar beet growth and, therefore, at all nitrogen levels a high sugar yield level, similar to the 1976 yield level, was reached (Fig. 36). At the lower nitrogen levels, sugar yield in System B1 was much less than in Systems A and C, which had about the same yield. But at higher nitrogen levels ($>$ 120 kg ha^{-1}) sugar yields were similar in all three systems. Sugar contents in System C

Table 55. Precipitation (mm) during weeks I/VIII before, and after sowing of sugar beet.

Spring	Tillage system	Sowing date	Before sowing							After sowing		
			I	II	III	IV	I/IV	V/VIII	I/VIII	I/IV	V/VIII	I/VIII
1976	A, C	24/3	2	16	0	5	23	17	40	19	4	23
	BI	9/4	2	5	8	19	34	8	42	4	29	33
1977	A, C	22/4	2	12	32	19	65	33	98	55	25	80
	BI	24/5	6	23	9	17	55	54	109	20	21	41
1978	A, C, BI	17/4	28	0	2	26	56	47	103	64	21	85
1979	A, C, BI	19/4	1	10	7	26	44	104	148	95	111	206

Table 56. Plant number and relative emergence of sugar beet.

Year	Distance in the row (cm)	Number of plants per ha (× 10³)			Emergence (%)[a]		
		A	C	BI	A	C	BI
1976	8.2	133	138	126	54	56	52
1977	14.5	74	78	–	54	56	–
	12.0	–	–	103	–	–	62
1978[b]	15.5 (A, C)	–	–	–	–	–	–
	7.0 (BI)	–	–	–	–	–	–
1979	15.5	72	80	–	56	62	–
	11.0	–	–	122	–	–	67

a. Relative to the number of seeds sown.
b. In 1978 emergence counts were not made.

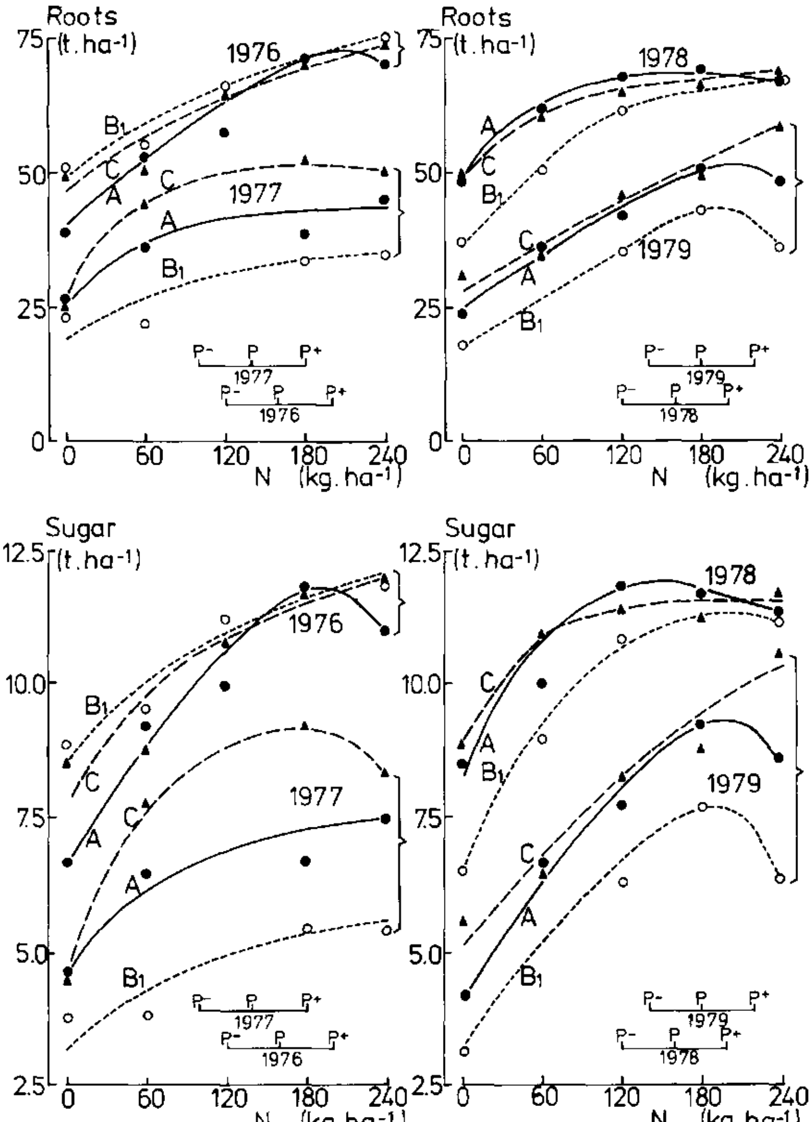


Fig. 36. Root yield and sugar yield of sugar beet at five nitrogen levels in separate years.

were slightly higher than in Systems A and B1 (Fig. 37).

In 1979 sugar yields in Systems A and C were similar, but in System B1 sugar yield was much lower at all nitrogen levels (Fig. 36). In all systems the yield level was much lower than in 1978 and of the same order of magnitude as in 1977. In all systems, crop response to nitrogen was pronounced, and in System B1 even an optimum was reached at 180 kg ha^{-1}. It is noticeable that in 1979 sugar contents were higher than in any other year of the period 1976 – 1979 and that the usual decrease in sugar content with increasing nitrogen applications did not occur (Fig. 37).

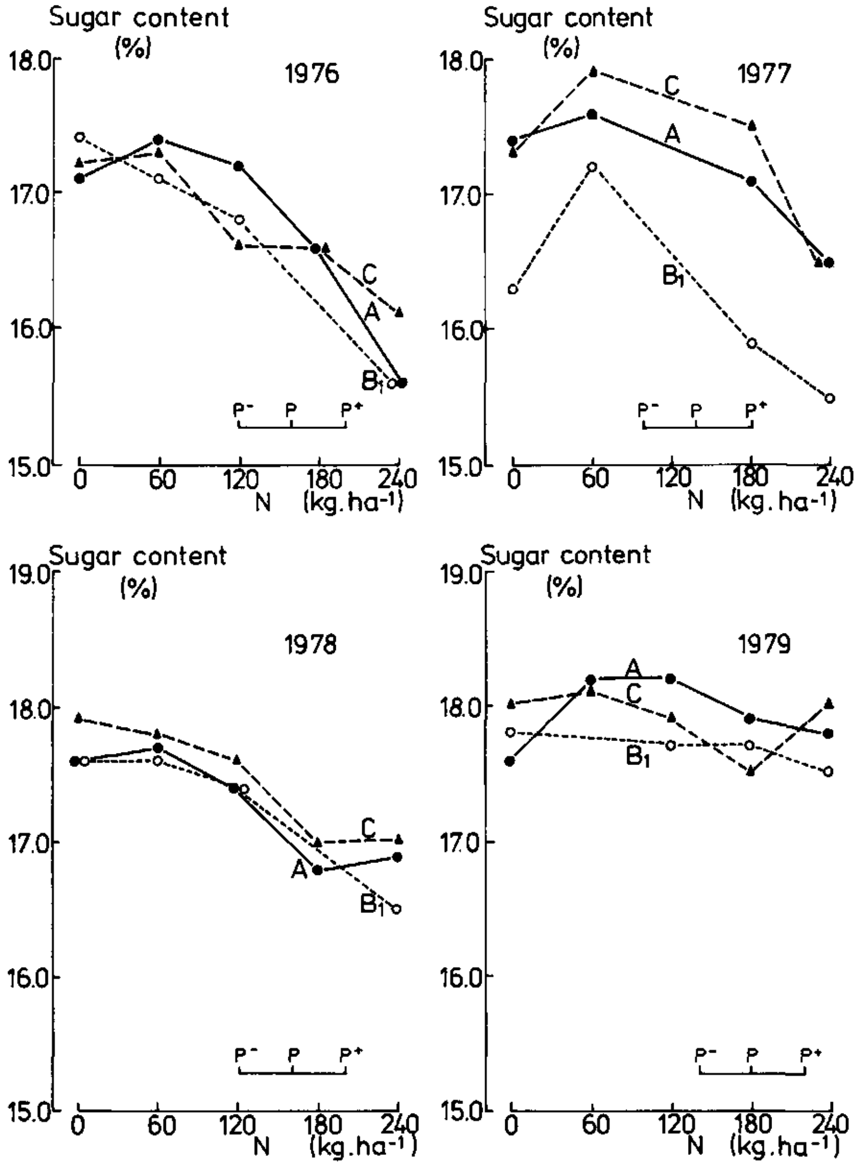


Fig. 37. Sugar content of sugar beet at five nitrogen levels in separate years.

7.4.4 Crop response to perennial nitrogen levels.

On average, in Systems A and C root yields and sugar yields were similar (Tables 57 and 58), but in System B1 root yield was 13% less and, due to a 0.4% lower sugar content (Table 59), sugar yield was 15% less than in Systems A and C.

Table 57. 1976 1979 average root yield and sugar content of sugar beet at three perennial nitrogen levels.

System	Yield relative to mean at nitrogen level (%)			Mean yield[a]		Yield relative to System C (%)	Sugar content (%)
	P	P	P+	(t ha^{1})	(%)		
A	97	99	104	57.2	104	98	17.2
B1	93	102	105	50.0	91	86	16.8
C	97	101	102	58.2	106	100	17.2
Mean	96	100	104	55.1	100	.	17.1

a. When 1977 is ruled out, mean root yields amount to 62.3, 56.9 and 62.8 t ha^{1} for Systems A, B1 and C, respectively, and total mean root yield amounts to 60.7 t ha^{1}.

Table 58. 1976 1979 average sugar yield at three perennial nitrogen levels.

System	Yield relative to mean at nitrogen level (%)			Mean yield[a]		Yield relative to System C (%)
	P	P	P+	(t ha^{1})	(%)	
A	99	99	102	9.8	104	98
B1	94	102	104	8.4	89	84
C	98	102	101	10.0	106	100
Mean	97	101	102	9.4	100	.

a. When 1977 is ruled out, mean sugar yields amount to 10.7, 9.6 and 10.8 t ha^{1} for Systems A, B1 and C, respectively, and total mean sugar yield amounts to 10.4 t ha^{1}.

Table 59. 1976 - 1979 average sugar content (%, w/w) at three perennial nitrogen levels.[a]

System	Nitrogen level			
	P–	P	P+	Mean
A	17.5	17.2	16.9	17.2
B1	16.9	16.8	16.7	16.8
C	17.4	17.3	16.9	17.2
Mean	17.3	17.1	16.8	17.1

a. When 1977 is ruled out, mean sugar contents amount to 17.3, 16.9 and 17.2% (w/w) for Systems A, B1 and C, respectively, and total mean sugar content amounts to 17.1% (w/w).

On average, the relative effect of nitrogen on root yield and sugar yield was clearly stronger in System B1 than in Systems A and C (Tables 57 and 58). However, in System B1 the negative effect of nitrogen on sugar content was much smaller (Table 59). At nitrogen level P – the difference in sugar content with Systems A and C was about –0.5%, and at nitrogen level P+ only –0.2%.

Differences in yield level between years were much larger than the differences caused by the effect of nitrogen within years (Fig. 38). In 1976 and 1978 yield levels were high: mean root yields amounted to about 65 t ha^{-1} and sugar yields to about 11 t ha^{-1} (Tables 60 and 61). The 1979 yield level was much lower: 51 t ha^{-1} roots and 8.9 t ha^{-1} sugar. In 1977 the yield level in Systems A and C was very low (about 43 t ha^{-1} roots and about 7.5 t ha^{-1} sugar) and in System B1, due to sowing one month later, extremely low (29 t ha^{-1} roots and 4.7 t ha^{-1} sugar).

The relative mean effect of nitrogen on root yield and sugar yield did not differ much between years, but for any one system the relative effect of nitrogen was clearly different between years. In Systems A and C, in 1976 the relative effect of nitrogen was about 10%, but in 1977 – 1979 only between 2 and -4%. In System B1, except for 1976 the effect was much stronger, especially in 1977 when yield level was extremely low (18%).

Sugar content always decreased with increasing fresh nitrogen applications but the rate of decrease was variable between years (Table 62). In 1977, in System B1 sowing was delayed for one month and, therefore, sugar content was much lower than in Systems A and C, and the effect of nitrogen was practically nil.

Generally, yield results obtained with perennial nitrogen levels and annual nitrogen levels were about the same. Therefore, the extremely low yield of roots and sugar in 1976 in System B1 at nitrogen level P+ must be considered an odd value.

Table 60. Root yield and sugar content of sugar beet at three perennial nitrogen levels.

Year	System	Yield relative to mean at nitrogen level (%)			Mean yield		Yield relative to system C (%)	Sugar content (%)
		P-	P	P+	(t ha^{-1})	(%)		
1976	A	93	100	108	65.1	100	95	16.8
	B1	99	105	97[d]	61.4	94	90	16.3
	C	92	100	107	68.6	106	100	16.5
	Mean	95	102	104	65.0	100	.	16.6
1977	A	97	102	101	41.8	109	94	17.0
	B1	91	99	110	29.2[a]	76[a]	66[a]	16.0[a]
	C	96	102	102	44.4	115	100	17.1
	Mean	95	101	104	38.5	100	.	16.8
1978	A	100[b]	97	102	68.5	103	102	17.2
	B1	90[b]	101	109[c]	63.7	96	95	17.1
	C	98[b]	101	100	67.1	101	100	17.5
	Mean	96[b]	100	104	66.4	100	.	17.2
1979	A	100[b]	97	104	53.3	105	101	17.7
	B1	91[b]	102	107	45.5	90	86	17.4
	C	101[b]	101	98	52.9	105	100	17.8
	Mean	97[b]	100	103	50.6	100	.	17.6

a. Sown one month later.
b. First repetition excluded.
c. Third repetition excluded.
d. Probably an odd value (see text).

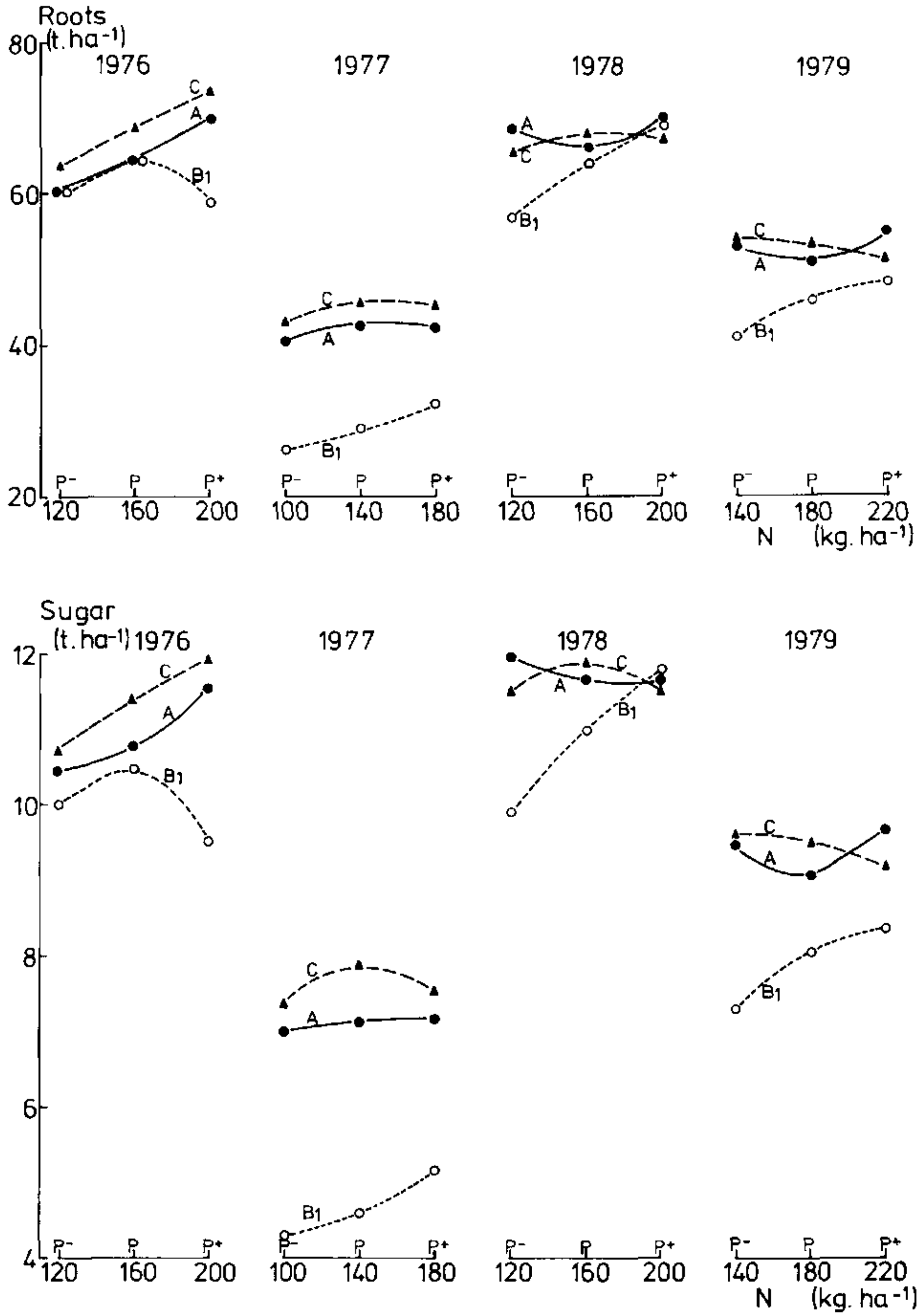


Fig. 38. Root yield and sugar yield at perennial nitrogen levels P−, P and P+, with indication of the fresh nitrogen dressings applied in separate years.

Table 61. Sugar yield of sugar beet at three perennial nitrogen levels.

Year	System	Yield relative to mean at nitrogen level (%)			Mean yield		Yield relative to System C (%)
		P-	P	P+	(t ha^{-1})	(%)	
1976	A	96	99	106	11.0	102	97
	B1	100	105	95[d]	10.0	93	88
	C	94	100	105	11.3	105	100
	Mean	96	101	102	10.8	100	.
1977	A	99	100	101	7.1	110	94
	B1	92	98	110	4.7[a]	72[a]	62[a]
	C	97	104	99	7.6	117	100
	Mean	96	101	103	6.5	100	.
1978	A	102[b]	99	99	11.8	103	101
	B1	91[b]	101	108[c]	10.9	95	93
	C	98[b]	102	99	11.7	102	100
	Mean	97[b]	101	102	11.5	100	.
1979	A	101[b]	96	103	9.4	106	100
	B1	92[b]	102	106	7.9	89	84
	C	102[b]	101	98	9.4	106	100
	Mean	98[b]	100	102	8.9	100	.

a. Sown one month later.
b. First repetition excluded.
c. Third repetition excluded.
d. Probably an odd value (see text).

Fresh nitrogen application at perennial nitrogen level P generally was about optimal, but in 1976 it was clearly sub-optimal. Therefore, in 1977 – 1979, in Systems A and C yields at nitrogen levels P–, P and P+ were about similar and only in 1976 there was a clear increase in yield from P- to P+ level. In System B1 there was always a clear positive effect of fresh nitrogen application but only in years when yield levels were high (1976, 1978) yield at P+ level was about the same as in Systems A and C.

Yield results obtained do not suggest cumulative effects of perennial nitrogen levels.

At harvest, the percentage of soil tare was considerable in all systems (Table 63). On average, in Systems A and C soil tare amounted to about 15% of gross yield. However, in System B1, due to more fanged roots, soil tare was about 21% of gross yield. This means that, on average, in Systems A and C the amount of soil tare was about 8.5 t ha^{-1} and in System B1 about 10.5 t ha^{-1}. Soil tare in System B1 was especially high in 1977 and 1979 (about 25% of gross yield), which is related to total precipitation during weeks I and II prior to sugar beet harvest (Table 64).

Table 62. Sugar content of sugar beet (%) at three perennial nitrogen levels.

Year	System	Nitrogen level			
		P–	P	P+	Mean
1976	A	17.2	16.7	16.5	16.8
	BI	16.5	16.4	16.2	16.3
	C	16.9	16.6	16.2	16.5
	Mean	16.9	16.5	16.3	16.6
1977	A	17.2	16.7	16.9	17.0
	BI	16.1[a]	16.0[a]	16.0[a]	16.0[a]
	C	17.2	17.3	16.6	17.1
	Mean	17.0	16.8	16.6	16.8
1978	A	17.5	17.6	16.8	17.2
	BI	17.4	17.2	17.1	17.1
	C	17.5	17.5	17.2	17.5
	Mean	17.4	17.4	17.0	17.2
1979	A	17.8	17.8	17.6	17.7
	BI	17.6	17.3	17.2	17.4
	C	18.0	17.8	17.7	17.8
	Mean	17.8	17.7	17.5	17.6

a. Sown one month later.

Table 63. Soil tare of sugar beet (% of gross yield).

Year	Tillage system		
	A	BI	C
1976	11.5	15.8	11.2
1977	14.4	24.4	14.8
1978	13.9	19.4	16.9
1979	18.5	25.3	16.9
Mean	14.6	21.2	15.0

Table 64. Precipitation (mm) during weeks I/IV prior to sugar beet harvest.

Year	Harvest date	Week						
		I	II	I/II	III	IV	III/IV	I/IV
1976	5/10	11	7	18	8	34	42	60
1977	12/10	12	14	26	0	2	2	28
1978	10/11	1	4	5	25	8	33	38
1979	20/11	10	38	48	30	2	32	80

7.5 Spring barley

7.5.1 Introduction

After sugar beet harvest, in Systems A, C and B1 the field was tilled shallowly (5 – 7 cm) with a spring-tine cultivator in a transverse direction to level the surface and spread the chopped sugar beet tops and leaves. In System B2, after harvest of the previous crop (1976: maize; 1977 – 1979: field beans), no tillage was performed; only weeds were sprayed with chemicals.

Primary tillage in System A consisted of ploughing to 25 cm depth, and in System C of fixed-tine cultivation to 15 cm depth which, in 1977 – 1979, was carried out across the field to reduce wheel slip. Depending on conditions, in both Systems A and C the soil was coarsely to very coarsely crumbled. In System B1 no primary tillage was performed.

In spring 1976 the soil was nicely weathered and dry (Table 65), which allowed seedbed preparation with a spring-tine cultivator. In System A this could be done with a normal spring-tine cultivator, and in one operation, whereas in Systems C and B1 two passes with a spring-tine cultivator with double chisel points were required. In System A, seedbed preparation and sowing were combined in one pass; in Systems C and B1 sowing was performed in a separate pass.

In 1977 – 1979, in all three Systems A, C and B1, seedbed preparation was done with a powered rotary harrow, which was combined with sowing in one pass (bridge-link). This procedure never posed any problems.

In Systems A and C always a reasonable to good, 5 cm deep seedbed was obtained. Usually in System C the seedbed was slightly coarser and shallower (about 4 cm). In System B1 the seedbed contained, as a rule, more coarse clods and was so shallow (2 – 3 cm) that sometimes the seed could hardly be sufficiently covered.

In System B2, spring barley was sown with the triple-disc drill in the stubble of the previous crop (1976: maize; 1977 – 1979: field beans), usually at the same date as in the other systems. However, in 1977 in System B2, sowing could only take place one month

Table 65. Precipitation (mm) during weeks I/VIII before, and after sowing of spring barley, 1976 – 1979.

Spring	Tillage system	Sowing date	Before sowing							After sowing		
			I	II	III	IV	I/IV	V/VIII	I/VIII	I/IV	V/VIII	I/VIII
1976	A, C, B1	6/3	5	2	0	16	23	31	54	32	5	37
	B2	8/3	0	6	0	15	21	31	52	32	5	37
1977	A	11/3	3	11	24	5	43	71	114	71	39	110
	C, B1	16/3	10	4	18	20	52	54	106	67	40	107
	B2	20/4	7	9	30	19	65	41	106	56	23	79
1978	A, C, B1, B2	5/4	0	13	34	18	65	11	76	71	22	93
1979	A, C, B1, B2	13/4	7	10	25	5	47	101	148	92	93	185

later than in Systems A, C and B1 because the triple-disc was initially not available and later on rainy weather prevailed for a long time (Table 65).

As a rule, sowing was not a problem in System B2. However, in 1976 the soil was superficially frozen and, therefore, the triple-disc drill could not penetrate the soil deep enough. Subsequent harrowing to improve the incomplete covering of the seed did not have the desired effect. In contrast, in 1979 the soil was so wet that the slots were smeared and so much soil adhered to the discs that a 'ploughing' effect was obtained.

7.5.2 Crop development

In 1976 and 1977 the cultivar Aramir was grown; in 1978 and 1979 the cultivar Pirouette was grown (Table 66). The seed rate in Systems A, C and B1 was in each year the same, but in System B2 on average 23% more seed was used. In 1976 – 1978 the seed rate was about the same, but in 1979, after less satisfactory results in 1978, in all systems the seed rate was increased by about 25%.

In all systems emergence was usually satisfactory, but in System B1, and especially in System B2, emergence was irregular, which was partly due to the uneven surface inducing slaking and suffocating of seedlings in dips (1977: System B1). In System B2 in 1977, when sowing had to be delayed for one month, many seedlings were prey to pheasants and, therefore, in spite of the 23% higher seed rate, the number of plants per square metre was 12% less than in Systems A and C. In the favourable spring of 1976, in System B2 the number of plants per gram of seed was only 8% lower, but in 1977 – 1979 it was on average 19% lower than in Systems A, C and B1.

Crop development in Systems A and C was always satisfactory and with only small differences between these systems. Generally, crop development in System B1 was less satisfactory and less regular; in system B2 it left much to be desired. However, there were clear differences between years, which are also apparent in the grain yield data.

Table 66. Seed rate and plant density of spring barley.

		A	C	B1	B2
Seed rate (kg ha^{-1})	1976	70	70	70	90
	1977	75	75	75	85
	1978	70	70	70	90
	1979	90	90	90	110
Plants per m^2	1976	128	130	130	154
	1977	146	153	130	131[a]
	1978	116	124	127	140
	1979	167	169	163	151
Plants per gram of seed	1976	18.3	18.6	18.6	17.1
	1977	19.5	20.5	17.3	15.4
	1978	16.6	17.7	18.1	15.6
	1979	18.6	18.8	18.1	13.7

a. Sown one month later; bird damage in Repetition II not considered.

7.5.3 Crop response to annual nitrogen levels

As a rule, grain yields in Systems A and C were similar (Fig. 39). In the dry year 1976, in System B1, and especially in System B2, at the lower nitrogen levels grain yields lagged behind, but at levels of 80 kg ha^{-1} yields about equalled those in Systems A and C. The growing season of 1977 was much wetter but crop response to nitrogen and yield levels did not differ much from those in 1976. In Systems A, C and B1 (except at zero nitrogen levels) grain yields were about the same, but in System B2, due to sowing one month later and severe bird damage, grain yield was substantially less. In 1978, grain yields were similar for all systems, but crop response to nitrogen differed significantly from previous years because at nitrogen levels >40 kg ha^{-1} grain yields decreased substantially. In 1979, yield data were incomplete but it is apparent that grain yields in Systems A and C were about the same, whereas in System B2, due to sowing into a too wet soil and, consequently, an irregular stand of the crop, grain yield was about 14% less. For System B1 the data on grain yield is too scanty to draw a conclusion.

7.5.4 Crop response to perennial nitrogen levels

During 1976 – 1979, yield levels of spring barley did not differ much between years (Table 67), except for System B2, where yield in 1977 was very low, due to sowing one month later than in the other systems (Table 67). Between Systems A and C yield differences were negligibly small, and on average these systems yielded only slightly higher than System B1 (Table 68). Averaged for 1976 – 1979 spring barley grain yield in

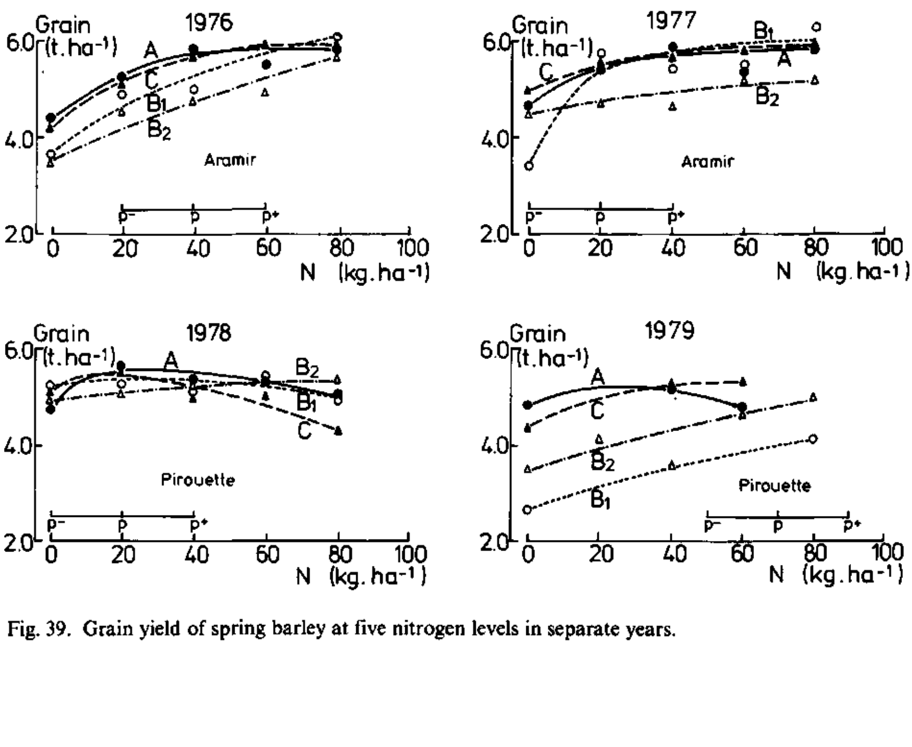


Fig. 39. Grain yield of spring barley at five nitrogen levels in separate years.

Table 67. Grain yield of spring barley at three perennial nitrogen levels.

Year	System	Yield relative to mean at nitrogen level (%)			Mean yield		Yield relative to System C (%)
		P	P	P+	(t ha^{-1})	rel. (%)	
1976	A	90	102	108	5.5	105	98
	B1	85	98	117	4.9	94	88
	B2	80	101	119	4.9	93	87
	C	92	102	106	5.6	107	100
	Mean	87	101	112	5.2	100	
1977	A	91	102	107	5.4	112	102
	B1	86	108	106	4.8	98	90
	B2	95	96	109	4.0[a]	81[a]	75[a]
	C	96	97	107	5.3	109	100
	Mean	92	101	107	4.8	100	
1978	A	103	103	93	4.9	98	96
	B1	101	100	99	5.2	103	101
	B2	94	103	104	4.9	98	96
	C	99	100	101	5.1	101	100
	Mean	99	102	99	5.0	100	-
1979	A	103	102	95	5.6	102	106
	B1	100	100	100	5.6	102	106
	B2	96	100	104	5.4	99	103
	C	99	104	97	5.3	97	100
	Mean	99	101	99	5.4	100	-

a. Sown one month later than in Systems A, B1 and C.

Table 68. 1976 1979 average yield of spring barley at three perennial nitrogen levels.

System	Yield relative to mean at nitrogen level (%)			Mean yield[a]		Yield relative to System C (%)
	P	P	P+	(t ha^{-1})	rel. (%)	
A	97	102	101	5.3	104	100
B1	93	101	105	5.1	99	96
B2	91	100	109	4.8	93	90
C	97	101	103	5.3	104	100
Mean	95	101	104	5.1	100	.

a. When 1977 is ruled out (System B2 sown one month later), mean yields amount 5.3 (A), 5.2 (B1), 5.1 (B2) and 5.3 (C) t ha^{-1}.

System B2 was 6% lower than in System B1 but when 1977 is ruled out, the difference was only 3%.

On average, crop response to nitrogen in Systems A and C was only small: between nitrogen levels P− and P+ the difference in mean yield was 4% and 6%, respectively

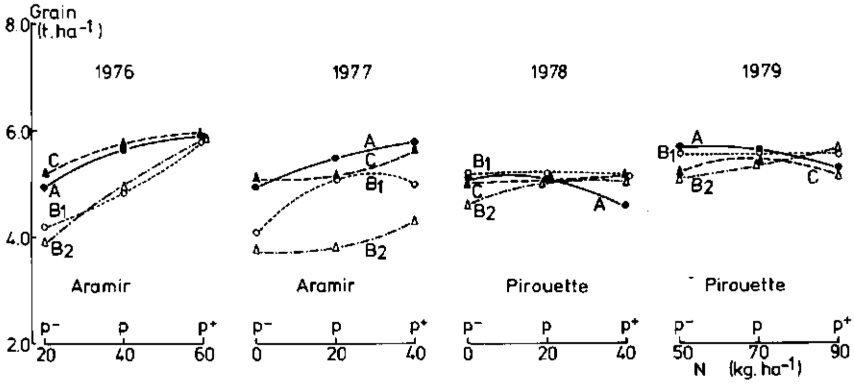


Fig. 40. Grain yield of spring barley at perennial nitrogen levels P–, P and P+, with indication of the fresh nitrogen dressings applied in separate years.

Table 68). However, in System B1, and especially in System B2, the effect of nitrogen was much stronger: between P– and P+ the difference in mean yield was 8% and 18%, respectively. It is interesting to note that within anyone year at the highest level of fresh nitrogen application there usually was no significant difference in grain yield between tillage systems.

Between years, there were large differences in crop response to nitrogen. In 1976 and 1977 the effect of nitrogen was much stronger than in 1978 and 1979. It appears that this difference is due to the fact that fresh nitrogen applications at P level were clearly sub-optimal in 1976 and 1977, and about optimal in 1978 and 1979, although between these years the level of fresh nitrogen applications differed very much (1978: low; 1979: high).

It may, therefore, be concluded that differences in yield level and nitrogen response between years were due to differences in both weather conditions during the growing season and level of fresh nitrogen application. It remains, therefore, questionable if perennial nitrogen levels had any cumulative effect on crop yield.

7.6 Discussion

During the period 1976 – 1979 the average crop yield level was about the same as during the period 1972 - 1975, with the apparent exception of potatoes, which yielded 27% lower (Table 69). However, this difference is due to the effect of planting one month later in System B1 in 1977 (2%), the very dry growing season of 1976 (10%) and the difference in the definition of 'saleable' yield in the first (tubers >35 mm) and the second (tubers >40 mm) crop rotation (15%).

In the 1972 - 1975 period, with the exception of spring barley, crop response to perennial nitrogen levels, i.e. the difference in relative yield at P+ and P–, was small or even negative (sugar yield). However, in the 1976 – 1979 period the nitrogen effect was much stronger, again with the exception of spring barley, for which it was about the same as in the 1972 – 1975 period. The similar nitrogen effect with spring barley may be due to

Table 69. Mean yield response to three perennial nitrogen levels, averaged for all systems, expressed as percentage of the mean yield of each crop, during 1972 – 1975 and 1976 – 1979[a].

Crop	1972 – 1975					1976 – 1979				
	P–	P	P+	Mean		P–	P	P+	Mean	
				t ha⁻¹	rel. (%)				t ha⁻¹	rel. (%)
Potatoes (saleable)[b]	98	100	102	52.7	100	95	100	105	38.3	100
Winter wheat (grain)	99	98	101	6.2	100	96	101	103	6.5	100
Sugar beet (roots)	99	102	99	58.6	100	96	100	104	55.1	100
Sugar beet (sugar)	101	101	97	9.7	100	97	101	102	9.4	100
Spring barley (grain)	96	100	105	4.7	100	95	101	104	5.1	100

a. Crop failure excluded; negative effect of sowing too late (Systems B1 and B2) included.
b. During 1972 – 1975: tubers > 35 mm; during 1976 – 1979: tubers > 40 mm.

the fact that in both periods the level of fresh nitrogen application (Table 70) was far below optimum, which means that yields obtained refer to the steep part of the nitrogen response curve, as indicated by the yield response curves of the annual nitrogen levels.

In the first crop rotation the difference in relative yield at perennial nitrogen levels P– and P+ was very variable (Table 71). In the second crop rotation, for potatoes, sugar beet and spring barley, the relative yield increase from P– to P+ nitrogen level was distinctly larger for System B1 than for System C; for winter wheat it was similar for Systems B1 and C. For winter wheat, sugar beet and spring barley, crop response to nitrogen was about the same for Systems A and C (3 – 5%), but for potatoes it was much stronger in System A than in System C (11% and 7%, respectively). For the cereals in System B2, especially for winter wheat, crop response to nitrogen was much stronger than in System B1.

In Systems A and C yields of sugar beet and cereals were about the same (Table 72). However, in System A potato yield was 6% less than in System C, which demonstrates that, generally, seedbed preparation and planting in one pass (System A) is not favourable for crop development. In System B1 cereal yields were only 4% less than in System C. With respect to spring barley this is in contrast with the first crop rotation, where this crop in System B1 yielded 17% less than in System C. Root crop yields were about 10% less in System B1 than in System C. For potatoes this accords with the first crop rotation but for sugar beet it means an improvement of 10%. Thus, it is not unreasonable to suggest that, generally, in System B1 availability of nitrogen was better in the second than in the first crop rotation. Still, 10% lower root crop yields are unacceptable. It should be noted that in Table 72 the years when crops failed were excluded. If these years are included, System B1 becomes still more unattractive for root crops.

When only years without crop failure are considered, yields of winter wheat and spring barley in Systems B1 and B2 were similar (Table 73). This is understandable, because if sowing with the triple-disc drill goes well, i.e. the slots are not smeared, and the seed is adequately covered, seedling growth is mainly governed by the soil structure below drilling depth. In Chapter 3 it was concluded that this soil structure was similar for both

Table 70. Average nitrogen fertilization (fresh application; kg ha⁻¹) at perennial nitrogen levels during 1972 - 1975 and 1976 - 1979.

Crop	1972 - 1975			1976 - 1979		
	P–	P	P+	P–	P	P+
Potatoes	190.0	240.0	290.0	200.0	247.5	295.0
Winter wheat	65.0	85.0	105.0	60.0	80.0	100.0
Sugar beet	120.0	157.5	195.0	120.0	160.0	200.0
Spring barley	22.5	40.0	57.5	17.5	37.5	57.5

Table 71. Average yield increase from perennial nitrogen levels P– to P+, relative to mean yield (%), during 1972 - 1975 and 1976 - 1979.

Crop	1972 - 1975				1976 - 1979			
	A	C	B1	B2	A	C	B1	B2
Potatoes (tubers)[a]	6	4	1	–	11	7	10	–
Winter wheat (grain)	3	6	-3	5	6	5	4	16
Sugar beet (roots)	10	2	-11	–	7	5	12	–
Sugar beet (sugar)	5	0	-15	–	3	3	10	–
Spring barley (grain)	10	3	14	19	4	6	12	18

a. During 1972 – 1975: > 35 mm; during 1976 - 1979: > 40 mm.

Table 72. 1976 - 1979 average crop yield, relative to crop yield in System C (%), average of three perennial nitrogen levels.

Years averaged	Crop	A rel.	B1 rel.	C	
				rel.	t ha⁻¹
1976, 1978, 1979	Potatoes (tubers > 40 mm)	94	88	100	41.0
1977 - 1979	Winter wheat (grain)	102	96	100	6.8
1976, 1978, 1979	Sugar beet (roots)	99	91	100	62.8
	Sugar beet (sugar)	99	89	100	10.8
1976 - 1979	Spring barley (grain)	100	96	100	5.3
Average[a]		99	92	100	

a. For sugar beet: sugar yield.

Table 73. 1976 - 1979 average grain yield of winter wheat and spring barley in Systems B1 and B2, average of three perennial nitrogen levels.

Years averaged	Crop	B1		B2	
		t ha⁻¹	rel. (%)	t ha⁻¹	rel. (%)
1977, 1979	Winter wheat	6.3	100	6.0	95
1976, 1978, 1979	Spring barley	5.2	100	5.1	98

systems. It means that, even after 8 years, yield results of 'pure' no-tillage were not as good as with extremely reduced tillage (seedbed preparation only; System B1).

During 1976 – 1979, for all crops, fresh nitrogen applications at P+ level were lower than the highest annual nitrogen level and, generally, even at the highest annual nitrogen level a clear optimum yield was not attained. Consequently, on average, to obtain the optimum yield at P level, the fresh nitrogen application at P level should have been increased to at least the amount which was actually applied at P+ level. The annual nitrogen levels show that at higher fresh nitrogen applications yield differences between tillage systems tend to become smaller or even to disappear. Therefore, in Systems B1 and B2, fresh nitrogen applications should be at least 20% higher than normally applied on ploughed fields.

During the second crop rotation weather conditions during the growing season and fresh nitrogen applications at perennial nitrogen levels differed very much from year to year. From the comparison of yield results obtained with annual nitrogen levels it appears that perennial nitrogen levels sometimes were clearly sub-optimal and sometimes about optimal. It is, therefore, not feasible to conclude about possible cumulative effects of perennial nitrogen levels.

7.7 Conclusions

1. During the period 1976 – 1979, yield levels were about the same as during the period 1972 – 1975, but crop response to nitrogen at the perennial nitrogen levels was much stronger. Differences in yield level between years were due to differences in both weather conditins during the growing season and in the level of fresh nitrogen application. It remains, therefore, questionable if perennial nitrogen levels did have any cumulative effect on crop yield.

2. For all main crops, sugar beet, potatoes, spring barley and winter wheat, yields in Systems A and C usually were similar. However, in 1976 and 1978 potato yields in System A were lower by 6% and 10%, respectively, than in System C.

3. In system B1 winter wheat failed in 1976 because of severe soil slaking but during 1977 – 1979 crop yields was, on average, only 4% less than in Systems A and C. Spring barley never failed and crop yield in System B1 was, on average, only 4% less than in Systems A and C.

4. In System B1, potato and sugar beet yields, averaged for 1976, 1978 and 1979, were about 10% lower than in System C. In 1977, when in System B1 planting of potatoes and sowing of sugar beet had to be delayed for one month, the differences were 39% and 34%, respectively. Therefore System B1 is unacceptable in a rotation with root crops.

5. In System B2, winter wheat failed in 1976 and nearly failed in 1978. In 1977 and 1979, winter wheat yield was 5% less than in System B1. In 1977 sowing of spring barley had to be delayed for one month and, therefore, yield was 25% less than in System C. However, in the other three years the spring barley yield was only 2% less than in System C. Thus, generally, even for cereals in a non-root crop rotation, 'pure' zero-tillage is not attractive.

6. With respect to crop yield loose-soil husbandry has not been shown to be superior to rational tillage. For potatoes and sugar beet loose-soil husbandry as practiced here is riskier than rational tillage.

7. Reduced tillage (seedbed preparation only) may give about the same cereal yields as rational tillage, provided nitrogen fertilization is adequate. However, for winter wheat following potatoes there is a serious chance of crop failure. Reduced tillage for root crops almost certainly leads to at least 10% lower yields than rational tillage.

8 Soil conditions and growth of spring barley on a tilled and untilled marine loam soil

F.R. Boone, B. Kroesbergen & A. Boers

8.1 Introduction

From the results of the first crop rotation (1972 - 1975), it appeared that when plant density was sufficient and nitrogen fertilization adequate, grain yield of winter wheat was identical for tilled and untilled soil. The growth of spring barley, however, was not so abundant on untilled soil, although at high nitrogen dressings differences in yields between tilled and untilled soil usually were small. Therefore, in 1978 and 1979 the effects of tillage-induced changes in soil water, soil aeration and mechanical impedance on root and shoot growth of spring barley were studied in detail. The research was carried out in the two tillage systems with the largest differences in soil structure, viz. System A (loose-soil husbandry) and System B1 (no-tillage with root crops), and in System B2 (no-tillage without root crops) where, unlike System B1, no seedbed was prepared.

8.2 Materials and methods

8.2.1 Introduction

In the autumn of 1977, in Systems A and B1, the soil, with sugar beet tops and leaves, was cultivated with a spring-tine cultivator to a depth of 5 cm. In System B2 the straw of the previous field beans was spread by hand. In the beginning of November, System A was ploughed to a depth of 25 cm under favourable soil conditions. On 5 April 1978 spring barley (c.v. Pirouette) was sown, in Systems A and B1 at the rate of 70 kg ha^{-1} and in System B2 at the rate of 90 kg ha^{-1}. In all systems 15 kg ha^{-1} English ryegrass was mixed through the spring barley seed. In System A nitrogen fertilization, seedbed preparation with a powered rotary harrow (working depth 3 - 4 cm) and sowing were combined into one pass. In System B1, seedbed preparation with the powered rotary harrow and sowing were combined, whereas in System B2 the triple-disc drill was used.

In the autumn of 1978, in System B2 the straw of the previous field beans was chopped and spread at harvest. In System A, after sugar beet harvest under wet soil conditions, the soil together with sugar beet tops and leaves on the surface, was ploughed to a depth of 25 cm under favourable soil conditions in mid-November. System B1 was cultivated with a fixed-tine cultivator with duck-feet chisels to a depth of 5 cm. In all systems nitrogen fertilizer was applied on frozen soil in late winter and on 13 April 1979 seedbed preparation and sowing of spring barley were performed in the same way as in 1978, although spring barley seed rates were increased by 20 kg ha^{-1} in all systems.

In both years nearly all research was carried out on the subplots with the annual nitrogen level N3 (40 kg ha^{-1}) of repetition I, which was close to the normal amount of nitrogen used in agricultural practice in this region.

8.2.2 Meteorological data and soil physical determinations

Daily rainfall, minimum and maximum air temperature and open-pan evaporation were obtained from the E.H.F. Westmaas. Groundwater table depths were measured frequently in each plot in 3 m deep perforated pipes. Pore spaces and moisture retention curves were determined by applying standard techniques to at least ten 100 cm^3 undisturbed core samples from all relevant soil layers. Depending on the rainfall pattern, soil moisture contents were determined at least once a week, or more frequently if thought necessary, by augering at different locations at 10 cm depth-intervals (down to 80 cm) and by determining gravimetric moisture contents of composite mixed samples. During germination and emergence, in addition soil water contents of the 0 – 2, 2 – 4 and 4 – 10 cm layers were determined. In 1978 saturated hydraulic conductivities ($K_{sat.}$) were determined with the method described by Bouma (1977). In 1979, tensiometers (in duplicate) were placed at depths of 15, 25, 35 (ploughpan) 60 and 95 cm, respectively. Soil water potentials were measured with a pressure transducer (Bakker 1978) on the same dates at which gravimetric water contents were determined.

The aeration status of the soil was characterized by the oxygen concentration of soil air and oxygen diffusion rate (O.D.R.). Oxygen concentrations were determined polarographically when water content was high enough to give a marked response. Diffusion chambers (1 cm^3; 5 replicates) were placed at depths of 10 (Systems B1 and B2 only), 20, 40 and 70 cm, respectively. The O.D.R. was measured at depth intervals of 10 cm (10 replicates) with a slightly modified method of Letey and Stolzy (1964). The effective voltage was –700 mV, the platinum needles were 1 mm thick and 7 mm long. Soil temperature was measured (in duplicate) in 1979 at depths of 5, 10 and 20 cm. Penetrometer resistances down to 80 cm were measured in the field at 10 spots with a recording penetrometer (van Soesbergen & Vos, 1971) at several soil moisture contents (cone-base 1 cm^2, 60° total included angle).

8.2.3 Root and shoot growth

On several occasions, root lengths were measured by taking soil cores (100 cm^3, 10 replicates) within the seed rows at different depths. The soil was dried at 50°C and washed carefully on a fine sieve (0.3 mm openings), cleaned by hand and stored in alcohol (96%). At a later date, root lengths were determined by the number of intersections on a grid (Newman, 1966). Once root diameters of a great number of roots were measured with a microscope at small magnification. The numbers and lengths of roots from germinated seeds were measured 6 and 13 days after sowing in 1979. Rooting patterns were observed at profile walls using a slightly modified method of Reymerink (1964) at several dates during the 1979 growing season. The number of shoots that had emerged were counted on several dates during emergence on 2 or 3 sub-plots of 1 m^2 each. After emergence, shoot fresh and dry weights were determined in duplicate from 1 m^2 plots on four dates during the growing season. The numbers of plants harvested were counted when possible. Later on, fertile and non-fertile haulms were separated and ear weights determined. To test the influence of nitrogen on these parameters, all five annual nitrogen levels were harvested at two dates in 1979.

8.3 Results

8.3.1 Soil structure

The ploughed soil of System A and the surface layer of System B1 were much looser and had higher water contents at - 10 kPa (pF 2.0) than the untilled soil of System B1 and B2 (Table 74). In System B1, therefore, there was a big difference in soil structure between the seedbed and the dense untilled soil underneath.

In both 1978 and 1979 the lowest part of the ploughed soil (22 - 27 cm) had a weaker consistency and higher water content at pF 2.0 than the soil above this layer. In 1979 a somewhat higher pore space was also found in the 22 - 27 cm layer. In 1978, these effects

Table 74. Mean ($\bar{X}$)[a] and mean standard deviation ($\bar{S}_x$)[b] of pore space (%, v/v), water content at pF 2.0 (%, w/w) and air content at pF 2.0 (%, v/v) during the growing season of 1978 and 1979 at locations the research was carried out in spring barley.

	Depth (cm)	System A		System B1		System B2	
		1978	1979	1978	1979	1978	1979
Pore space							
$\bar{X}$	2 - 7	48.7	49.2	47.7	47.9	42.9	44.9
	12 - 17	46.6	47.1	40.5	40.2	40.3	42.0
	22 - 27	46.9	48.9	41.8	41.4	41.7	41.6
	32 - 37	39.6	40.4	41.5	42.0	41.7	43.9
$\bar{S}_x$	2 - 7	2.2	2.7	2.7	3.7	1.5	2.1
	12 - 17	2.0	2.7	1.0	1.0	1.2	1.3
	22 - 27	2.5	4.6	1.6	2.1	1.5	1.2
	32 - 37	1.0	1.4	1.2	0.7	2.2	1.4
Water content at pF 2.0							
$\bar{X}$	2 - 7	24.9	24.1	26.7	26.3	24.9	26.2
	12 - 17	24.0	23.5	22.2	21.4	22.5	23.4
	22 - 27	26.1	26.8	22.9	22.5	23.4	22.8
	32 - 37	21.7	23.1	24.4	24.8	23.7	26.0
$\bar{S}_x$	2 - 7	1.0	0.8	1.0	3.0	1.3	2.3
	12 - 17	0.7	1.1	0.7	0.5	0.9	1.1
	22 - 27	1.8	3.3	0.8	1.2	1.2	0.8
	32 - 37	0.6	1.0	1.0	0.6	2.5	1.3
Air content at pF 2.0							
$\bar{X}$	2 - 7	14.6	16.5	10.4	11.3	4.9	6.4
	12 - 17	12.4	13.9	5.2	6.0	4.4	5.8
	22 - 27	9.9	12.3	6.2	6.2	5.3	6.0
	32 - 37	4.3	3.4	3.1	3.4	4.6	4.6
$\bar{S}_x$	2 - 7	3.3	4.3	3.9	3.5	1.0	1.7
	12 - 17	2.8	3.7	1.1	1.2	0.8	1.3
	22 - 27	3.2	5.0	2.0	1.9	1.2	1.2
	32 - 37	1.0	0.9	1.0	0.6	0.6	1.0

a. n = 20 - 30.
b. n = 2 - 3.

were caused by ploughing down the fixed-tine cultivated top 5 cm with tops and leaves of the previous sugar beet crop. At the 1978 sugar beet harvest the top layer of the soil, in particular, was wet and partly puddled. The soil could not be cultivated before ploughing and as a result, in the 1979 growing season, the sugar beet trash and puddled soil were present as a layer in the lowest part of the ploughed layer. As a consequence, the difference in soil structure with the very dense ploughpan underneath was very large.

In Systems B1 and B2 the greatest soil density (with a small standard deviation) of the whole soil profile was found at a depth of 12 - 17 cm. Also, the water content at pF 2.0 was smallest in this layer. Air content at pF 2.0 was only 4.4 - 6.0% compared with about 13% for the same soil layer of System A. Except for 1979, when in the 12 - 17 cm layer of System B2 a small but significantly larger pore space was found, there were no differences between both systems in either the 12 - 17 cm or the 22 - 27 cm layers. The 32 - 37 cm layer (ploughpan) of System A was slightly denser than the corresponding layers of Systems B1 and B2. These differences were significant, except for System B2 in 1978. Air contents at pF 2.0 at ploughpan depth of all three systems were even smaller (3.1 - 4.6%) than in the untilled 12 - 17 cm soil layer of Systems B1 and B2. This can be partly explained by the water content prior to sampling which was generally higher at greater depths (see also Chapter 3).

Pore space of the soil below the ploughpan, with a porous spongy structure, was considerably larger than in the ploughpan and showed only minor variations between locations and depths. Between a depth of 47 and 102 cm mean pore space ($n = 50$) was 45.6% (v/v), water content at pF 2.0 was 25.1% (w/w) and air content at pF 2.0 was 8.9% (v/v). Mean standard deviations for every depth were very low (about 0.5%).

8.3.2 Germination and emergence

In both years at seedbed preparation and sowing, soil water content of the top 4 cm was higher in System B1 than in System A (Fig. 41). The seedbed of System B1 was more cloddy and somewhat more shallow than the seedbed of System A (Chapter 4). In 1979 seedbed preparation was delayed by a rainy period and soil water content was even higher than in 1978. However, at sowing, the untilled surface layer of System B2 always had the highest water content. In this system some mulch was present and much organic matter accumulated in the surface layer (Chapter 5), whereas, unlike System B1, after sugar beet harvest capillarity was not disturbed by tine cultivation. Consequently, especially in 1979 the walls of the seed furrow made by the triple disc were partly smeared.

In both years sowing was followed by a rainless period of 5 days. During this period in all systems the top 0 - 2 cm dried out very quickly to a soil water potential beyond - 1.6 MPa (pF 4.2). Water content of the 2 - 4 cm layer decreased more slowly. Soil water potential of System B2 even stayed close to - 10 kPa (pF 2.0). In 1979, six days after sowing, mean root length and number of roots of germinated seeds were smaller in System B2 than in System A (Table 75). Around this date, soil temperature measurements at a depth of 5 cm revealed that, although the amplitude was somewhat larger in System A than in System B2, mean values were nearly equal (Table 76). However, in System B2 seeds were not covered by a layer of aggregates and not all seeds were in close contact with the seed furrow. Moreover, this furrow was not fully closed at the surface. It

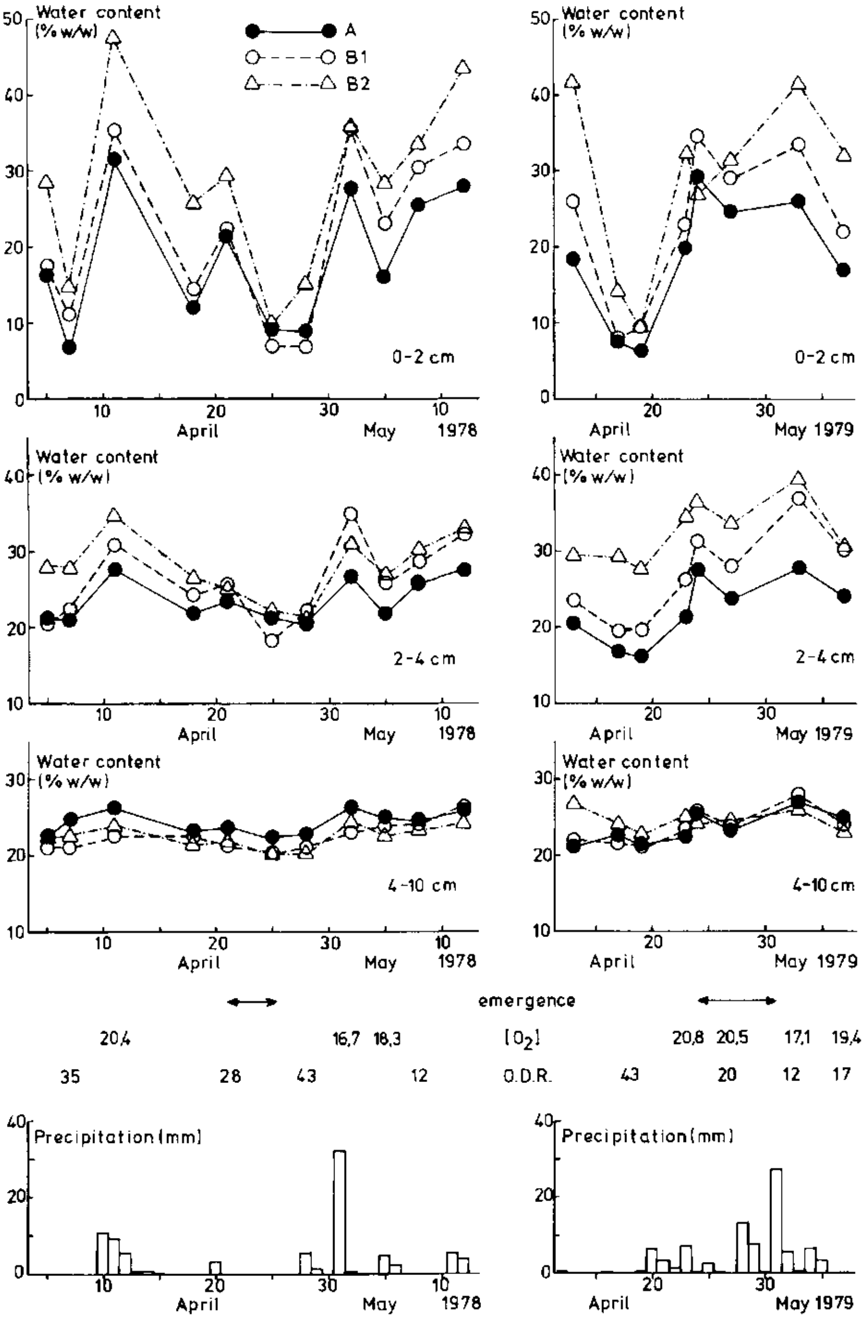


Fig. 41. Soil water content in and below the seedbed during germination and emergence of spring barley. Bottom: period of emergence, oxygen concentration (0_2; %, v/v) and oxygen diffusion rate (O.D.R.; 10^{-8} g cm^{-2} min^{-1}) in untilled soil at 10 cm depth, and precipitation.

Table 75. Mean root length, number of roots per plant and shoot length of spring barley, 6 and 13 days, respectively, after sowing in 1979.

Date	Root length per plant		Root number per plant		Shoot length	
	cm	relative	n	relative	cm	relative
19 April						
A	6.6	100	5.5	100	–	–
B1	5.0	76	4.8	87	–	–
B2	3.7	56	4.2	76	–	–
26 April						
A	30	100	5.6	100	5.2	100
B1	23	77	4.7	84	4.7	89
B2	19	63	4.9	88	3.3	62

Table 76. Soil temperature (°C) at a depth of 5 cm around the beginning of the emergence of spring barley in 1979.

Time	System	April						Mean
		19	23	24	25	26	27	
09.00	A	.	.	8.2	6.1	6.2	6.2	6.68
	B2	.	.	8.1	6.3	6.2	6.2	6.70
17.00	A	10.5	10.3	10.2	9.8	9.4	9.5	9.95
	B2	9.6	10.0	9.8	9.4	9.1	9.2	9.52

is therefore likely that water availability to the seeds was less and mean seed temperature higher than measurements show.

After the rainless period, rain (in 1978, 26 mm in 3 days, and in 1979, 20 mm in 4 days) increased water content at seed depth considerably. Temporarily soil water potentials were even less negative than −10 kPa. In some dips at the bottom of the seed furrows of System B2, water was observed. Although no information about the aeration status of the seeds is available, oxygen concentration and Oxygen Diffusion Rate (O.D.R.) in untilled soil of System B1 may give an indication (Fig. 41). It is likely that aeration was sufficient in the seedbeds of Systems A and B1 and in dips of the surface of System B2 at the bottom of the seed furrow it was only limiting for a short time. Because air and soil temperatures were low during these days (especially in 1978), biological activity should have been low and damage to germinating seeds was probably small.

In 1978, a second rainless period followed in which the 2 – 4 cm layer gradually attained a soil water potential of −20 to −30 kPa (pF 2.3 – 2.5). When there is a good contact between seed and soil this is still sufficient for rapid germination and emergence. Plants emerged between 16 and 20 days after sowing. Plant density was somewhat higher in System A than in both other systems (Fig. 42). However, because the amount of seeds sown in System B2 was 29% higher, emergence was 61% compared with 78 and 85% in System B1 and A, respectively. Variability in plant densities between sub-plots was considerable. Nevertheless it can be concluded that plant numbers were always sufficient. Heavy rainfall around the beginning of May did not influence the final plant number.

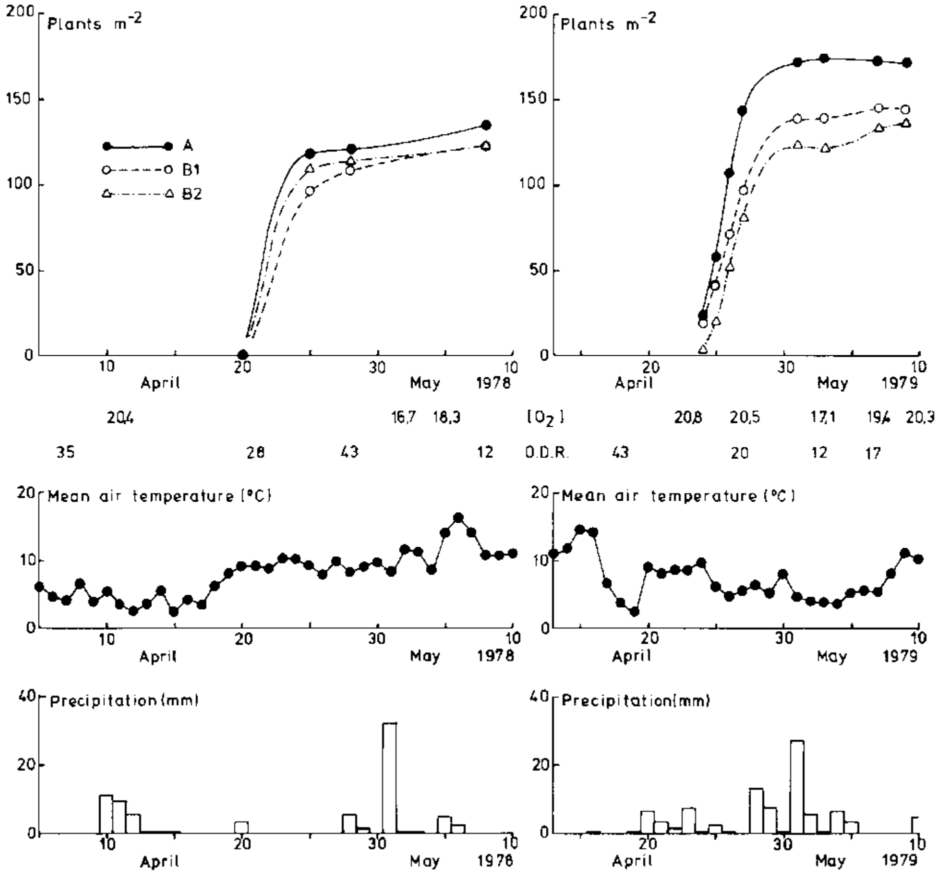


Fig. 42. Emergence of spring barley. Bottom: oxygen concentration (O_2; %, v/v) and oxygen diffusion rate (O.D.R.; 10^{-8} g cm^{-2} min^{-1}) in untilled soil at 10 cm depth, mean air temperature and precipitation.

In 1979, mean temperatures were somewhat higher than in 1978. Ten days after sowing, directly after the rainy days mentioned, emergence started. Emergence was somewhat faster in System A than in System B2. At the start of emergence, root and shoot lengths were significantly different between systems, with highest values for System A and lowest for System B2 (Table 75). For example, very long roots were absent in System B2 and most abundant in System A (Fig. 43). This may be attributed to the fact that roots have to penetrate the very dense soil surrounding the seed furrow. Roots of System B1 were in a better position because in the seedbed they easily could grow in all directions and penetrating the dense soil below the seedbed had more lateral support. Shoot length also was influenced only to a minor degree in this System.

The seedbed was still wet and emergence was not complete when a very wet period started. This induced an insufficient O.D.R. in the untilled soil of System B1. Soil temperature at depths of 5 and 10 cm decreased to about 5°C. This diminished soil respiration to a low level and, therefore, the soil oxygen concentration did not decrease

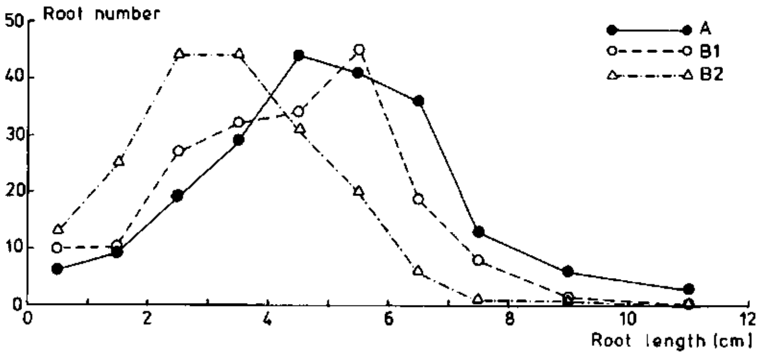


Fig. 43. Relationship between root number (n) and root length of spring barley (26 April 1979).

so strongly. After 27 mm of rain on 1 May, the seed furrows of System B2 contained water for several days. The smeared walls of the seed furrows conducted water only very slowly to deeper soil layers. In dips of the surface, runoff caused water to be ponded. This was also the case on the slaked surface of the seedbed of System B1. In System A, water ponded only for a short period in wheel tracks. The final result was that plant density was highest in System A and lowest in System B2. Due to the higher seed rate, plant density was still somewhat higher in 1979 than in 1978. Although 22% more seeds were sown in System B2, final percentage emergence was only 54 compared with 73 and 88% in System B1 and A respectively. Due to variability in topology and subsequent variability in adverse soil physical conditions, plant densities from spot to spot were quite irregular in Systems B1 and B2. Nevertheless, plant densities were regarded as sufficient for equal yield expectations in all systems.

8.3.3 Soil water

The saturated hydraulic conductivity showed values of 2 - 5 cm h^{-1} for the ploughed layers of System A, 1 - 2 cm h^{-1} for the untilled arable layer, 2 cm h^{-1} for the ploughpan and 5 cm h^{-1} for the soil below the ploughpan. Although the number of measurements was small and variability was large, they indicate that the saturated hydraulic conductivity was still acceptable even though this marine loam soil had not been ploughed for 7 years. The same was true for the ploughpan, whereas the soil below the ploughpan was very permeable.

Depths of the groundwater table were similar on tilled and untilled soil (Fig. 44). When the groundwater table was close to drainage depths (110 cm) it was usually a few cm deeper on tilled than on untilled soil. This may be largely accounted for by the small differences in surface level due to compaction of the untilled soil. Fluctuations in groundwater table depth were also similar on tilled and untilled plots. As an illustration, two examples will be given. After 32 mm of rain on 1 May 1978, groundwater table depth one day later was 42 and 60 cm, and four days later 84 and 81 cm in Systems A and B1, respectively. During the first rainy period in 1979 these figures were 40 cm and 38 cm one day after 27 mm of rain on 2 May, and 85 cm and 81 cm four days later. Later in the

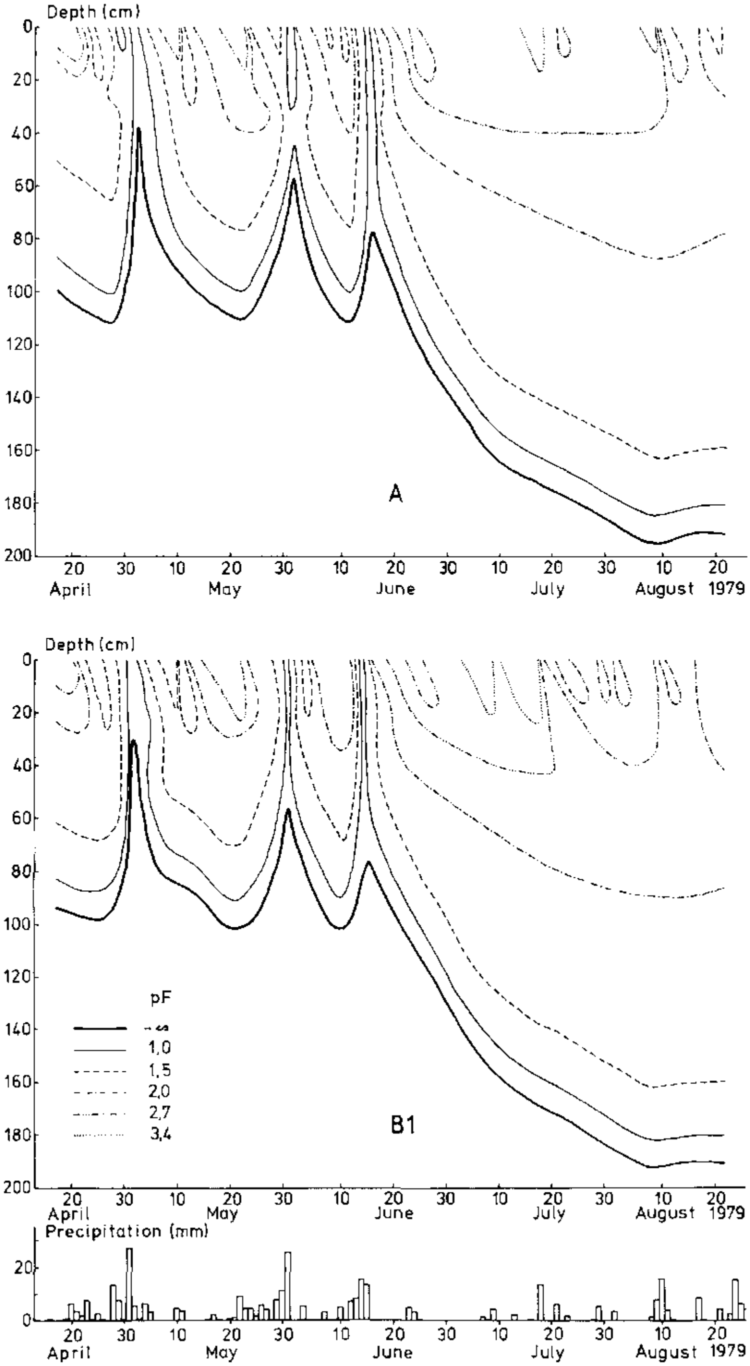


Fig. 44. Precipitation, groundwater table and soil water potentials in spring barley plots in 1979.

season, when the soil dried out, the groundwater table fell at an equal rate on both tilled and untilled soil.

Soil water potentials obtained during the very wet first part of the 1979 growing season (from 20 April – 20 June: 235 mm rainfall) also indicate that water movement was not seriously hampered in the soil, which had not been tilled for 8 years. In fact, water potentials were even remarkably similar (Fig. 45).

It is important to note that during a rainy period the soil water potential of the arable layer of this permeable and well-drained soil was considerably less negative than – 10 kPa for a number of days. During the first wet period (1 May) the arable layer was, temporarily, even almost saturated. At the end of June, the soil water potential at a depth of 25 cm perhaps decreased somewhat more slowly in System B2 than in both other systems, the result of the smaller number of roots at that depth. Obviously the ploughpan on both tilled and untilled soil was no barrier for water movement.

Especially after rainfall gravimetric water content of the 0 – 10 cm layer was usually somewhat lower on tilled than on untilled soil (Fig. 46). However, in the 10 – 20 cm layer, System A always had the highest water content. Due to water extraction by the plant roots this difference gradually became smaller at lower water contents, which can be explained by differences in the pF curves (Fig. 47). At soil water potentials close to zero, gravimetric water content was much higher on tilled than on untilled soil. This difference diminished at

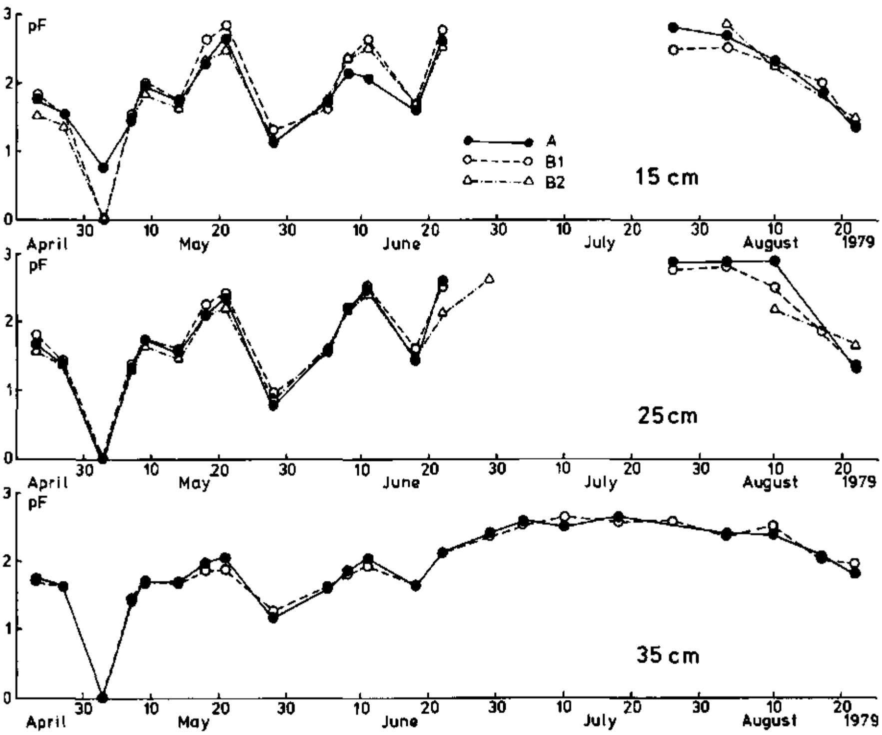
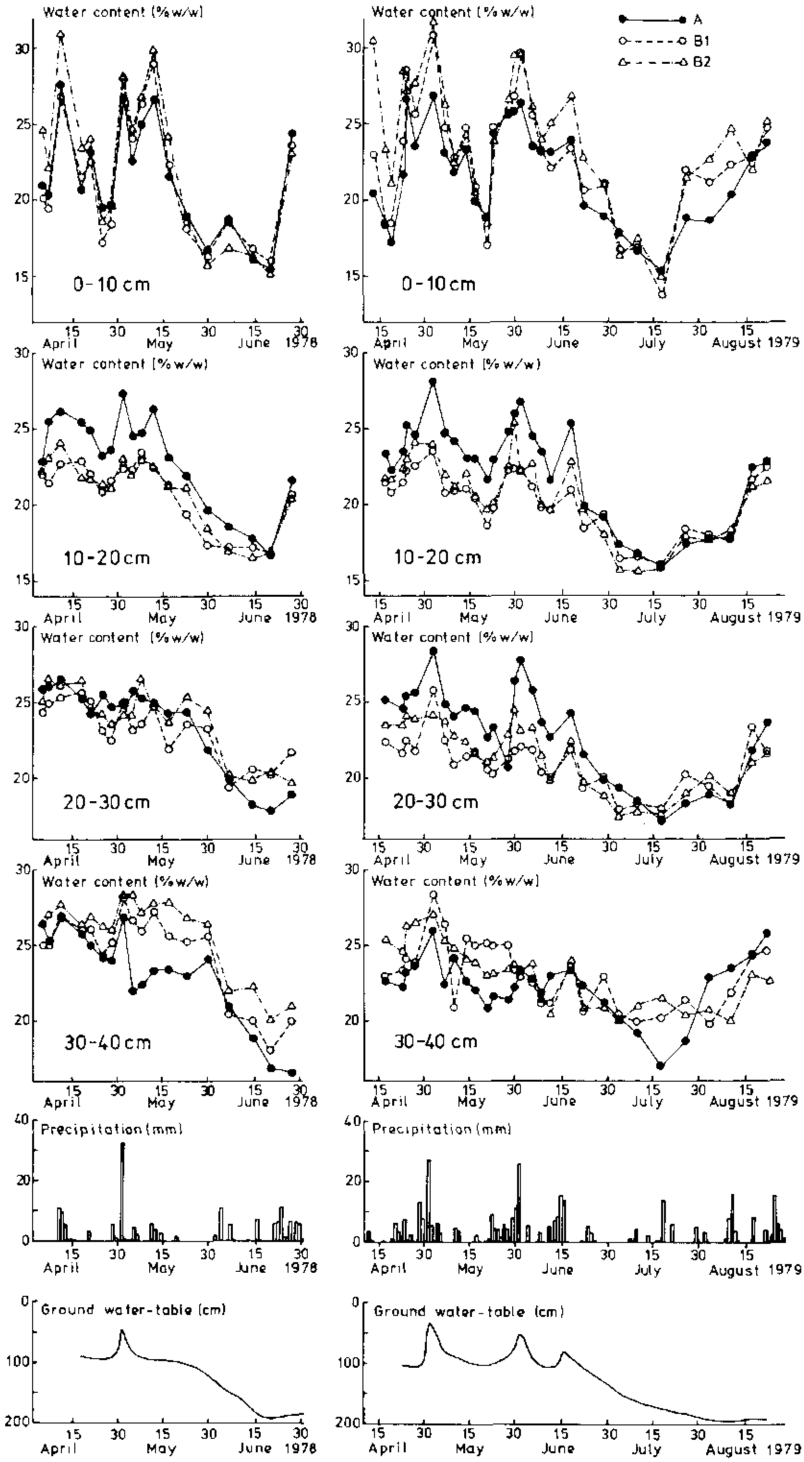


Fig. 45. Soil water potentials at 15, 25 and 35 cm depth in spring barley plots in 1979.


Water content (%w/w)
0-10 cm
10-20 cm
20-30 cm
30-40 cm
A
B1
B2
Precipitation (mm)
Ground water-table (cm)
April
May
June
July
August 1979
June 1978

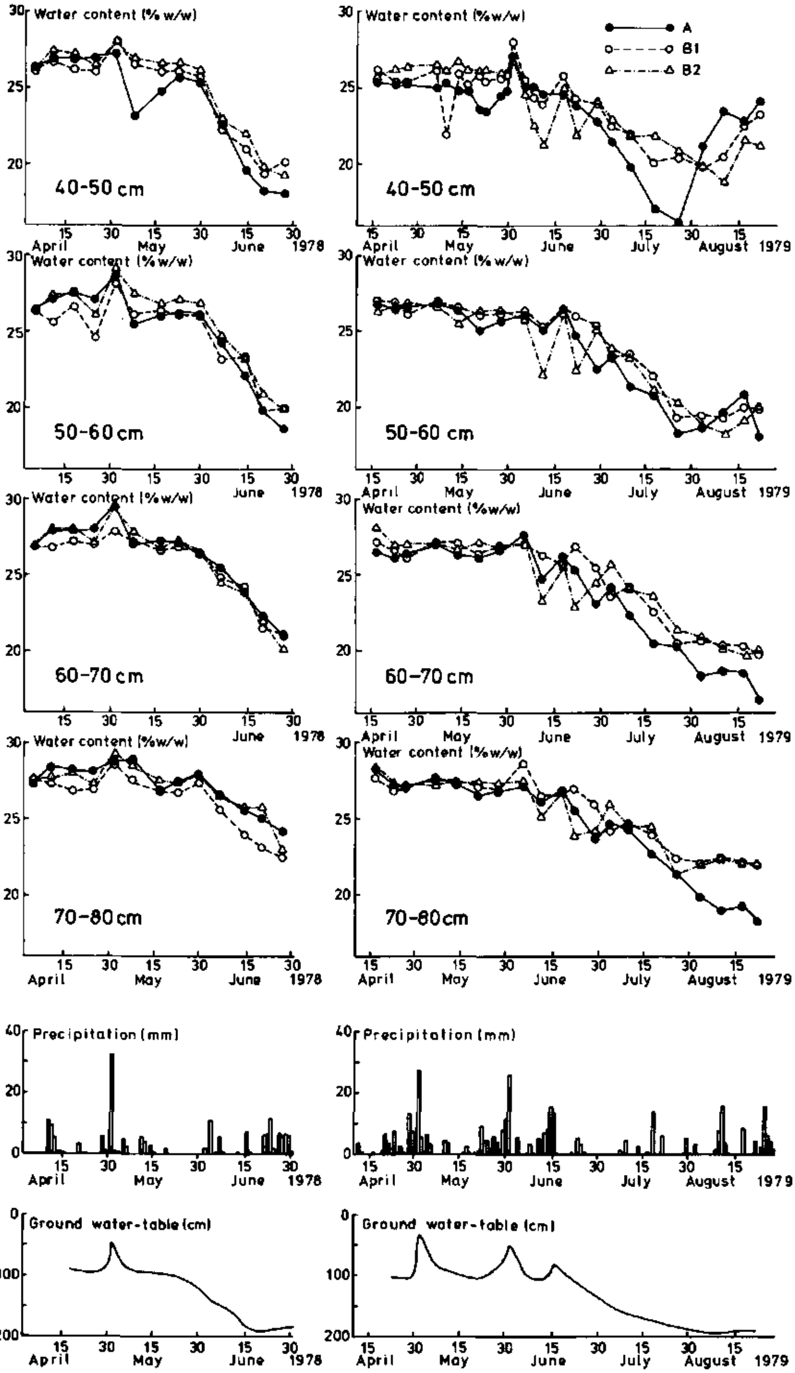


Fig. 46. Precipitation, groundwater table and gravimetric water content of several soil layers in spring barley plots in 1978 and 1979.

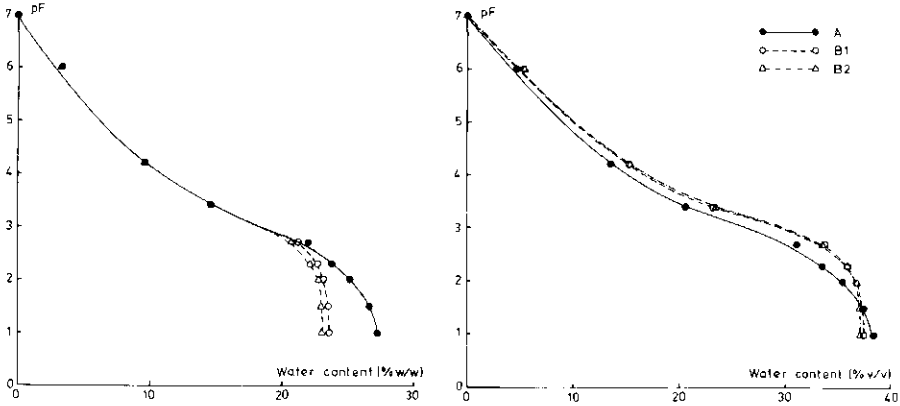


Fig. 47. Moisture retention curves for the 12 – 17 cm layer of spring barley plots. Left: gravimetric moisture content; right: volumetric moisture content.

more negative soil water potentials and is nearly absent at a soil water potential of −100 kPa. On a volumetric basis, differences in pF curves between tilled and untilled soil were smaller. Except for soil water potentials between 0 and −5 kPa volumetric water contents were a few percent higher on untilled soil. The amount of readily-available water (pF 2 – pF 2.7) was 3.1% (v/v) and 4.5% (v/v) on tilled and untilled soil, respectively, but there was no real difference in total available water (pF 2 – pF 4.2: 22.0% (v/v) and 21.5% (v/v), respectively). In System A the 20 – 30 cm layer included untilled and tilled soil and, especially in 1979, sugar beet debris. As a result, gravimetric water content in 1979 was higher in this system than in both other systems. The 30 – 40 cm layer included the ploughpan, which had a slightly smaller pore space in tilled than untilled soil, and had, therefore, at the beginning of the growing season a smaller gravimetric water content. Deeper in the soil profile, differences between systems were relatively small and inconsistent.

The first part of May 1978 was wet, but by mid-May the groundwater table was again at a depth of 100 cm and the arable layer close to field capacity. The first roots had just reached the ploughpan (Subsection 8.3.6). During the second half of May, with a potential evaporation of 46 mm and 1.7 mm of rainfall, the soil dried out. It appeared (Fig. 48) that in System A soil water was depleted in the 0 – 30 cm layer, but in Systems B1 and B2 only in the 0 – 20 cm layer. Water content decreased especially in the 0 – 10 cm layer of System B2, which coincided with a high concentration of roots. In all treatments soil water depletion in the first 3 weeks of June, with a potential evaporation of 91 mm and 27.3 mm of rainfall, was concentrated primarily in the C horizon. Compared with both other systems, in System A soil water depletion was somewhat larger in the 0 – 30 cm and somewhat less in the 60 – 80 cm layer. Total depletion in both periods was similar for all systems: 64.6, 61.3 and 64.8 mm for Systems A, B1 and B2, respectively. In System A, water depletion in both periods was fairly uniform to a depth of 60 cm. In Systems B1 and B2, total depletion in the A horizon decreased significantly with depth but was somewhat higher than in System A just below the ploughpan.

In 1979, rainfall prevented the soil from drying out before the second half of June, one

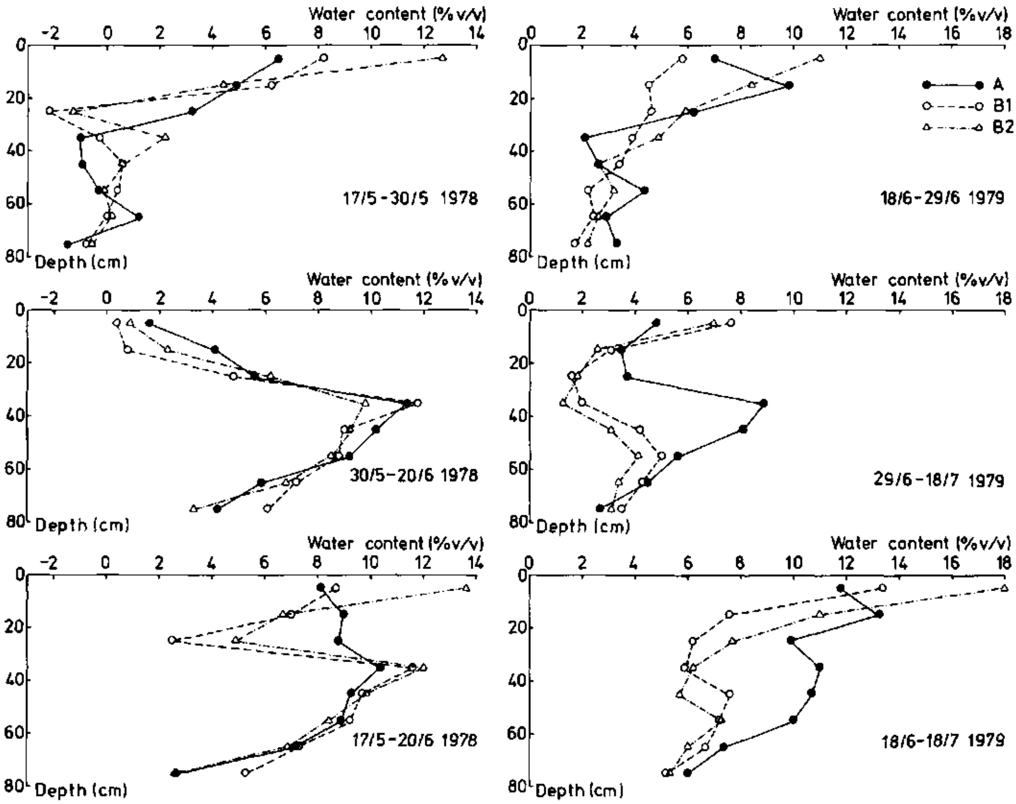


Fig. 48. Decrease in volumetric soil water content in spring barley plots during different periods in 1978 and 1979.

month later than in 1978. At that time, roots had already reached a depth of more than 70 cm, which is reflected in the soil water depletion at the start of this relatively dry period (with a potential evaporation of 98 mm and 20 mm rainfall). Soil water depletion in System B1 was less than in both other systems. Later on, when the topsoil had dried out to some extent, more water was absorbed from the soil below the ploughpan. Now water absorption was clearly higher in System A, primarily because in Systems B1 and B2 water absorption from the soil below the ploughpan was much smaller than in 1978. Total depletion in both periods was 80, 60 and 67 mm for Systems A, B1 and B2, respectively. Although there was a small dip at ploughpan depth, in System A total water depletion in both periods was again fairly uniform with depth. In August, the 60 – 80 cm soil layer was depleted more in System A than in both other systems.

8.3.4 Soil aeration

In the whole soil profile, oxygen concentrations were always higher in System A than in Systems B1 and B2. This was very clear during wet periods but only marginal at drier soil conditions (Fig. 49). Differences between Systems B1 and B2 were small and not

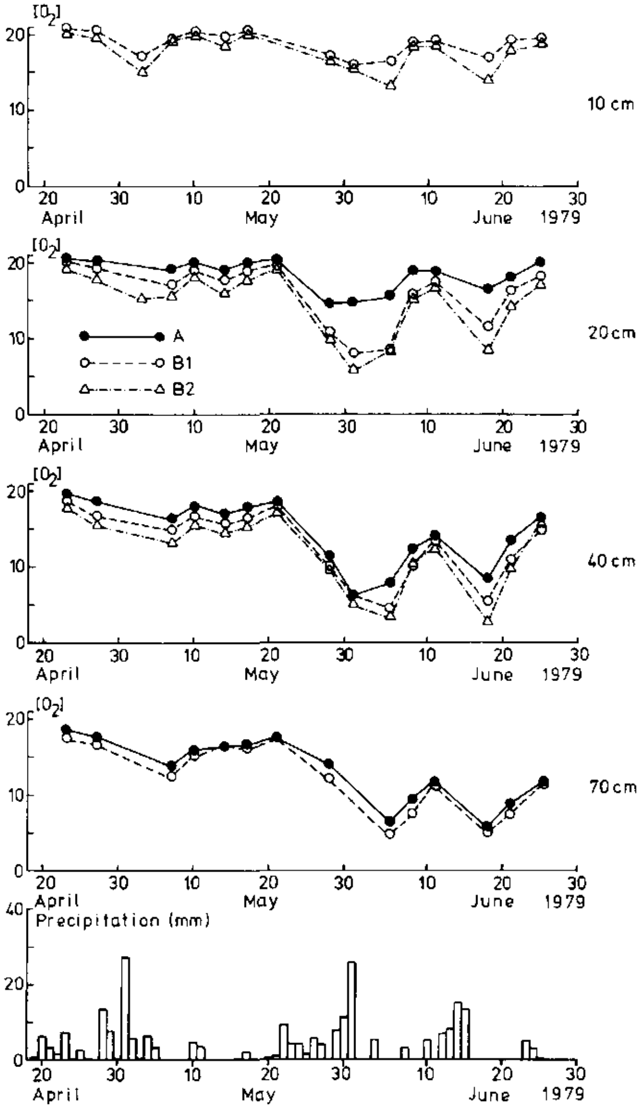


Fig. 49. Precipitation and soil oxygen concentrations at several depths in spring barley plots in 1979.

always consistent. In 1978, System B1 quite often had somewhat lower oxygen concentrations than B2, whereas in 1979 always the reverse was true.

In 1978, low oxygen concentrations (< 10%) were never measured, not even at a depth of 70 cm. In this layer, lowest concentrations were obtained after heavy rainfall at the beginning of the growing season. However, at that time, the oxygen consumption was still small, due to low soil temperatures and a very limited amount of roots. Later on, water contents steadily decreased and, therefore, gas diffusion strongly increased (Chapter 3). Oxygen concentrations as a result steadily increased. In untilled soil, oxygen concentrations at maximum rooting depth were always higher than 15%.

During the first wet period at the beginning of the 1979 growing season, oxygen concentrations were similar to those in the same period of 1978. In all systems soil water potentials were close to zero and some diffusion wells were filled with water. At the end of the second wet period, end May 1979, lowest oxygen concentrations were observed. At a depth of 20 cm concentrations were still 15% in System A, but only 6 - 8% in untilled soil. At a depth of 40 cm, just below the ploughpan, values were 6 - 8% and 3 - 6%, respectively. Between 20 and 40 cm, which included the ploughpan, the largest decrease in oxygen concentration was in System A. During the third wet period, the oxygen concentration in the arable layer decreased somewhat less than during the second wet period. This was due to a greater evapotranspiration, somewhat less rainfall and, therefore, lower soil water contents during the third period. Because at greater depths the number of roots was still relatively small, oxygen concentrations between the two periods were more similar.

In the arable layer, the roots at the rooting front have grown at a high oxygen concentration (Fig. 50). However, during the second wet period the roots at the rooting front of all systems, especially in Systems B1 and B2 have temporarily grown at oxygen concentrations below 10%. Nevertheless, in the C horizon root growth rate to depth was greater than in the ploughpan.

The mean Oxygen Diffusion Rate (O.D.R.) showed a large variability with time, especially in untilled soil. During wet periods and high soil water contents, mean O.D.R. of the untilled arable layer was $<20\ 10^{-8}\ g\ cm^{-2}\ min^{-1}$, which is considered to be insufficient (Letey & Stolzy, 1964). In the ploughed layer of System A, critical mean values were never obtained. Probably because in System A sugar beet trash and partly puddled soil were ploughed in, differences between tilled and untilled soil were greater at a depth of 10 cm than at a depth of 20 cm. From the relation between the soil water potential and O.D.R. it can be seen that critical values in loose soil can be expected only near saturation (Fig. 51). In the dense untilled soil of System B1, at a depth of 20 cm critical values were obtained at pF 1.2 and at ploughpan depth at pF 1.4. In the slightly more compacted ploughpan of System A, critical values were already obtained at pF 1.8.

Mean O.D.R. values, soil water contents, rainfall data and obtained relationships for each system and depth between O.D.R. and water content allowed the estimation of the length of the periods with insufficient O.D.R. (Fig. 52). During rainy periods, especially when evapotranspiration was small, critical periods were substantial at a depth of 10 cm in the untilled soil. In 1978 at 20 cm depth, critical periods were absent and in 1979 shorter than at 10 cm depth. The ploughpan and deeper soil layers, in particular, of all systems had a long period with an insufficient O.D.R.. In 1978 this period was somewhat shorter in System A than in both other systems. This may be due to the presence early in the season of many roots just above the ploughpan and subsequent higher uptake of water in System A. In the C horizon, roots at the rooting front of Systems B1 and B2 have grown at a still insufficient mean O.D.R.. As a result the vertical growth rate was smaller than in System A. In 1979 the soil in (at a depth of 30 cm) or just below (40 cm) the ploughpan of System A had an insufficient aeration until the end of the third period. In both other systems soil structure in these layers was somewhat better and showed a sufficient O.D.R. between subsequent wet periods. In 1979, however, root growth to depth was not slower than in 1978 (see also Subsection 8.3.6).

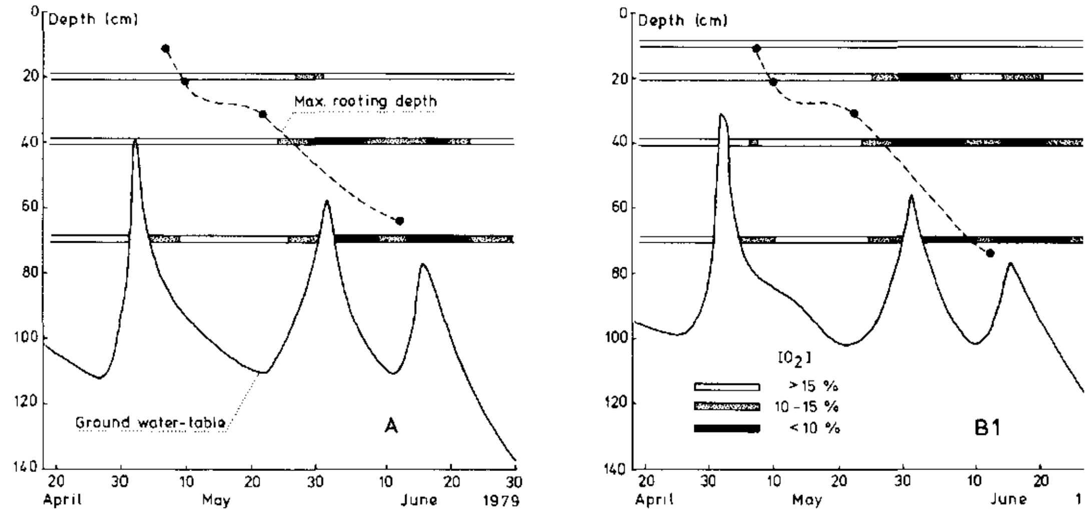


Fig. 50. Groundwater table, maximum rooting depth and soil oxygen concentrations in spring barley plots in 1979.

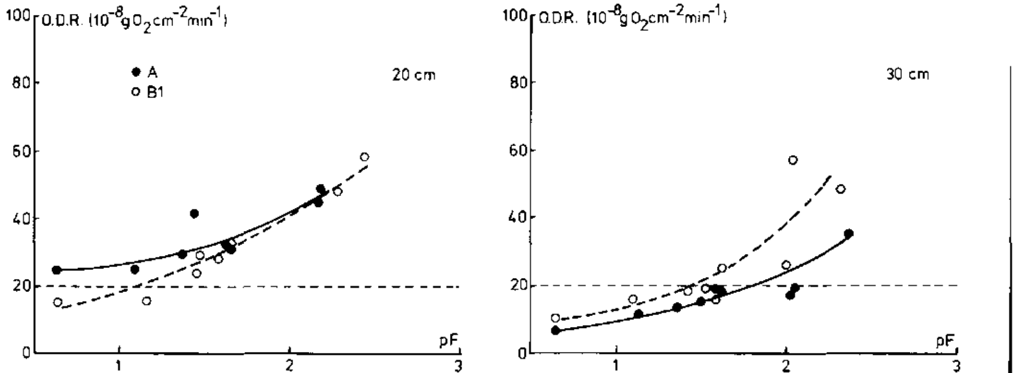


Fig. 51. Relationship between oxygen diffusion rate (O.D.R.) and soil water potential in the arable layer (20 cm depth) and ploughpan (30 cm depth) in spring barley plots in 1979.

8.3.5 Cone resistance

Relations were obtained for each system and depth between cone resistance and soil water content. These relations and the more frequently measured water contents made it possible to estimate cone resistance throughout the whole growing season (Fig. 53).

Mean cone resistance of the ploughed layer of System A was low for a long time. Except during wet periods, when cone resistance was lower than 1 MPa, it varied between 1-1.5 MPa. Cone resistance several weeks after the end of the last wet period exceeded 2 MPa in both years: at the end of May 1978 but not until the second week of

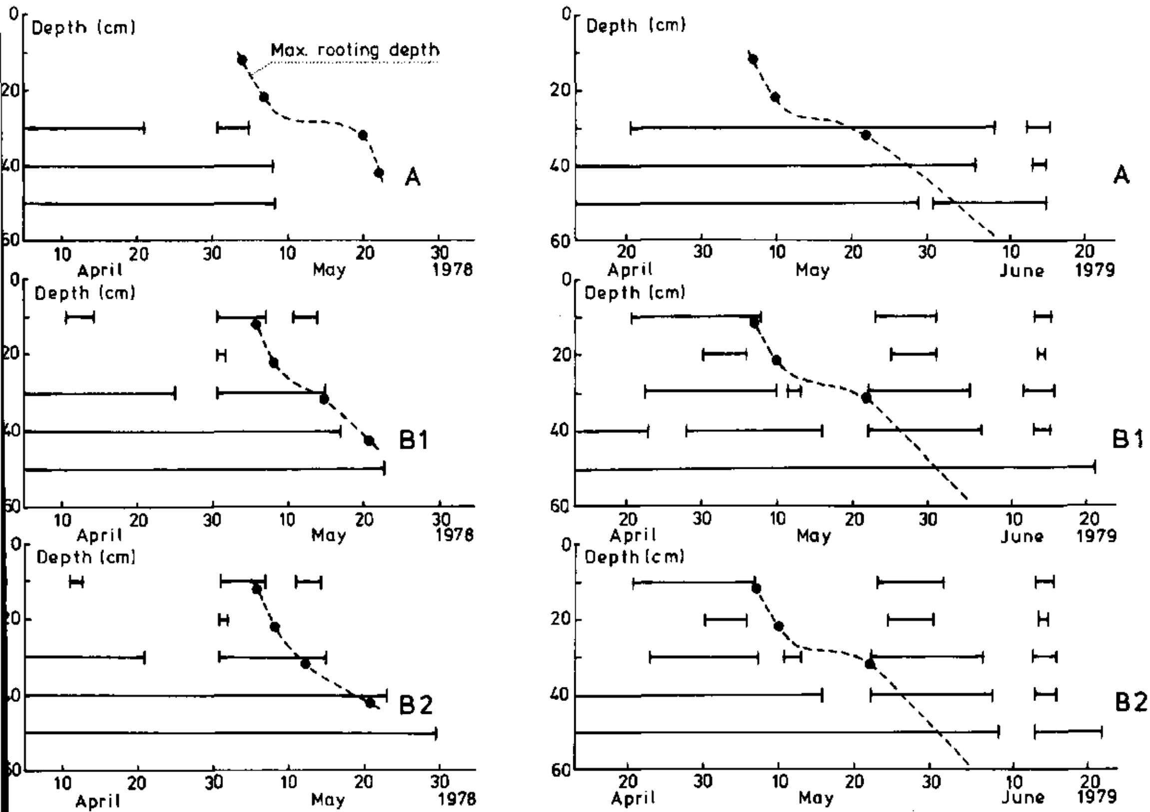


Fig. 52. Periods during which the oxygen diffusion rate (O.D.R.) was $< 20 \times 10^{-8}$ g cm^{-2} min^{-1} in spring barley plots in 1978 and 1979.

July 1979. At the beginning of the growing season cone resistance of the untilled arable layer of Systems B1 and B2 was about twice as high as in tilled soil. Because the inverse dependence of cone resistance on water content is much greater in a dense than in a loose soil (Boone et al., 1978), cone resistance fluctuated much more in untilled than in tilled soil. Although during wet periods cone resistance temporarily decreased below 2 MPa, only a small decrease in soil water content increased cone resistance above 3 MPa again. In 1978 this occurred about 2 weeks after the wet period at the beginning of May, and in 1979 1 week after the last wet period half of June. Shortly thereafter the 4 MPa level was passed.

At ploughpan depth, cone resistances of all three systems were comparable with the values obtained in the untilled arable layer. Because the root system and soil water extraction developed with time, cone resistance at ploughpan depth increased more slowly and to a somewhat lower maximum level than in the arable layers. In System A the 3 MPa and 4 MPa levels were passed earlier than in both other systems. This may be partly explained by a somewhat stronger developed ploughpan. This is reflected in a slightly higher cone resistance in spring, when the soil is in equilibrium with a ground-

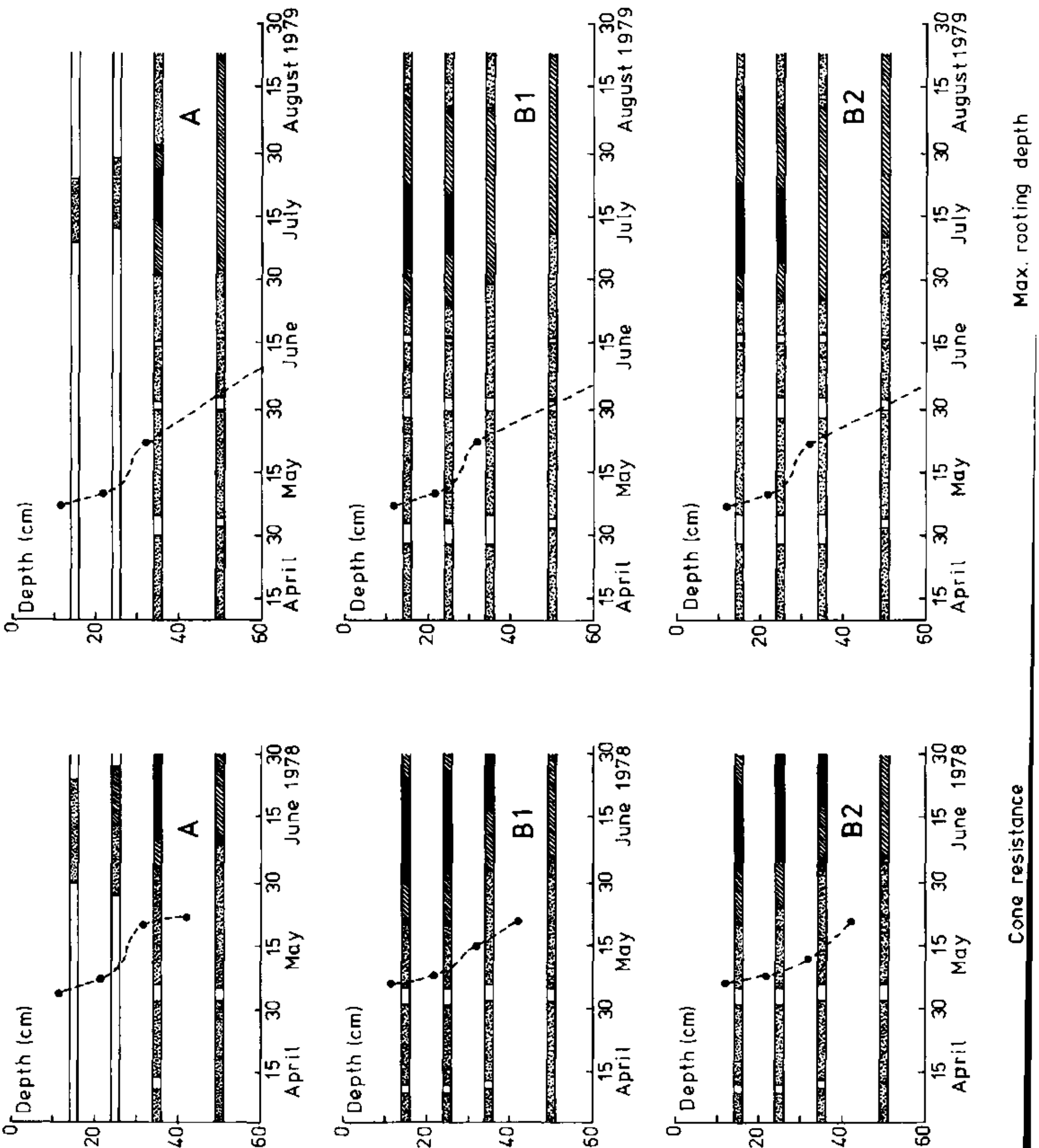


Fig. 53. Penetration resistance and maximum rooting depth in spring barley plots in 1978 and 1979.

water table of 1 m (Fig. 54). However, differences in root development also contributed in this respect (see also Subsection 8.3.6).

The soil below the ploughpan sometimes showed a considerable variability in cone resistance between different spots and depths. At the beginning of the growing season values were not significantly different from the other untilled soil layers. Because during the growing season the topsoil dried out more than the subsoil, maximum values were higher in the untilled topsoil than in the subsoil (Fig. 54).

In both years, root growth to depth proceeded at cone resistances close to values measured in spring, when soil is in equilibrium with a groundwater table at 1 m depth. However, in 1978 most root proliferation and branching occurred at lower soil water contents, and therefore, at high cone resistances in untilled soil layers. In 1979, in contrast, for more than one month root proliferation and branching occurred at relatively high soil water contents and intermediate cone resistances.

8.3.6 *Root growth*

In the arable layer, root growth to depth was not faster in tilled than in untilled soil (Fig. 55). Although in 1979, root growth to depth started a few days later, the root growth rate was about as fast as in 1978. The ploughpan, however, hampered root growth in all systems. In 1978 the transition from the loose ploughed soil to the very

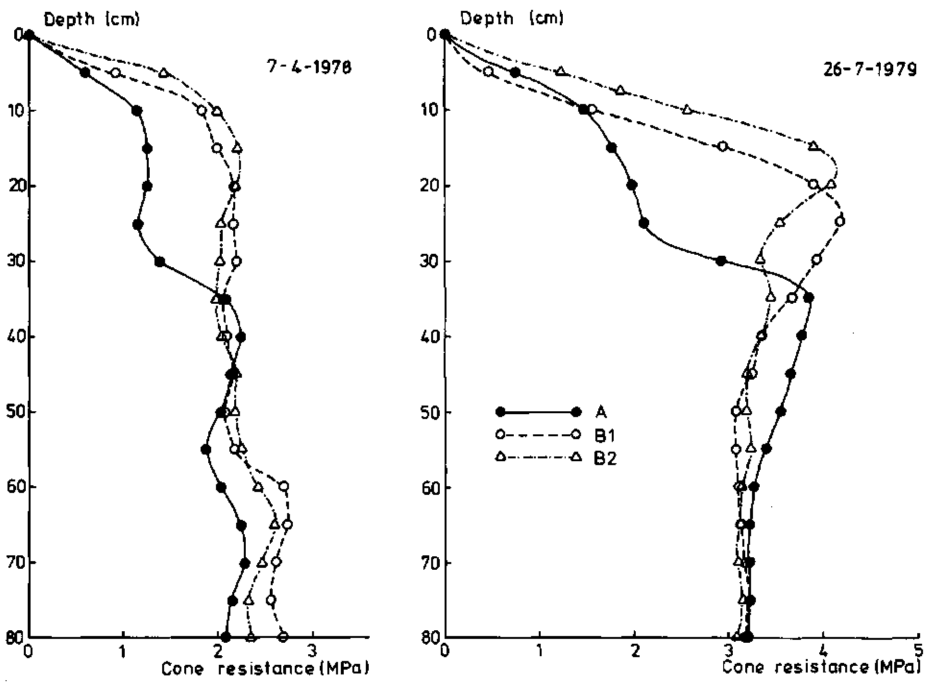


Fig. 54. Penetration resistance in spring (7/4/1978: soil moisture in equilibrium with a groundwater table of 1 m) and in summer (26/7/1979: relatively dry soil conditions) in spring barley plots.

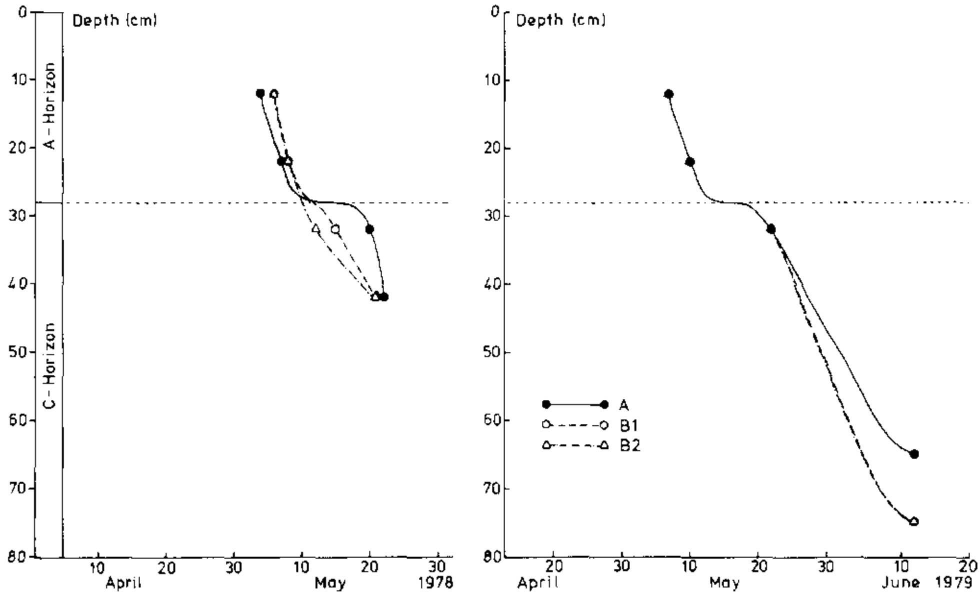


Fig. 55. Depth of the rooting front in spring barley plots in 1978 and 1979.

dense ploughpan in System A caused more problems than in both other sytems. In 1979, however, Systems B1 and B2 were hampered as much as System A. Below the ploughpan, the extension of the rooting front was nearly as fast as in the arable layer. Ultimate rooting depths were similar in all systems (Chapter 6).

During the first part of the growing season, root proliferation and branching was concentrated in the soil just below the seedbed (Fig. 56). The seedbed and the soil just below the seedbed in System B1 always contained more roots than in System A. In Systems B1 and B2 the number of roots in the arable layer decreased very sharply with depth, whereas in System A root distribution was more uniform. Although root counts on profile walls showed the same tendency, this was demonstrated most clearly by the quantitative root density measurements in soil cores (Fig. 57). Both methods were complementary because soil cores were taken only in plant rows in several characteristic soil layers. Root counts on profile walls could be made more rapidly and provided information on root development in the whole soil profile. On one occasion root counts at similar depths and distances from plant rows were compared with soil core data (Fig. 58). The profile wall method was sensitive at root densities <1 cm cm^{-3} but at higher densities small differences in root counts represented large differences in root densities. Counting roots may have been influenced by the amount of soil scraped away from the profile wall. Therefore the soil dry weight scraped away was determined from every soil layer. Because pore volume was known it could be concluded that, within the arable layer, about a 10% larger soil volume was explored in Systems B1 and B2 than in System A.

Until mid-June 1978, root density in the arable layer was higher in System B1 than in System B2 (Fig. 59). One month after emergence root density in System B2 was only

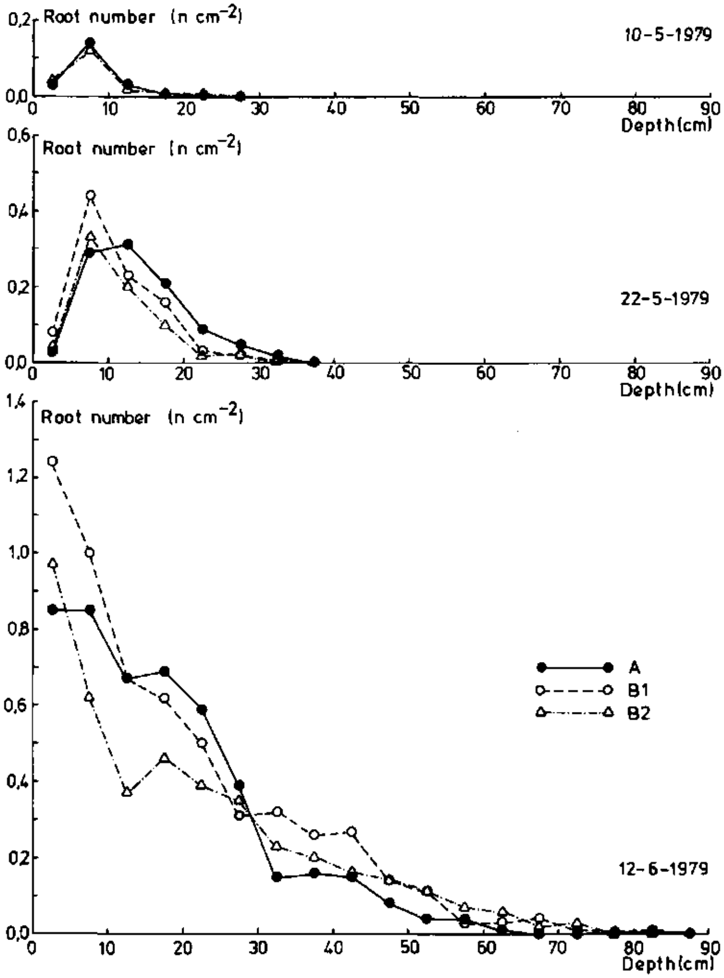


Fig. 56. Distribution of the number of roots counted on vertical profile walls with depth in spring barley plots in 1979.

about half of System A. In June, when the soil dried out, root growth decreased in System A, but after rainfall in the last ten days of June increased again. In contrast root growth in the untilled arable layer nearly ceased in June. In 1979 differences between System B1 and B2 were less clear than in 1978, although root counts on profile walls pointed in the same direction. At the end of May 1979, root density in the arable layer was considerably less than in 1978. This may be explained by a more slowly developing shoot. This also resulted in the rooting front arrived a few days later at any given depth.

The ploughpan hampered root penetration but also root proliferation and branching. At the end of May 1978, the ploughpan of System A had less roots than both other systems. In June, however, differences between systems faded away. In both Systems B1 and B2, root development in the soil below the ploughpan was faster than in the

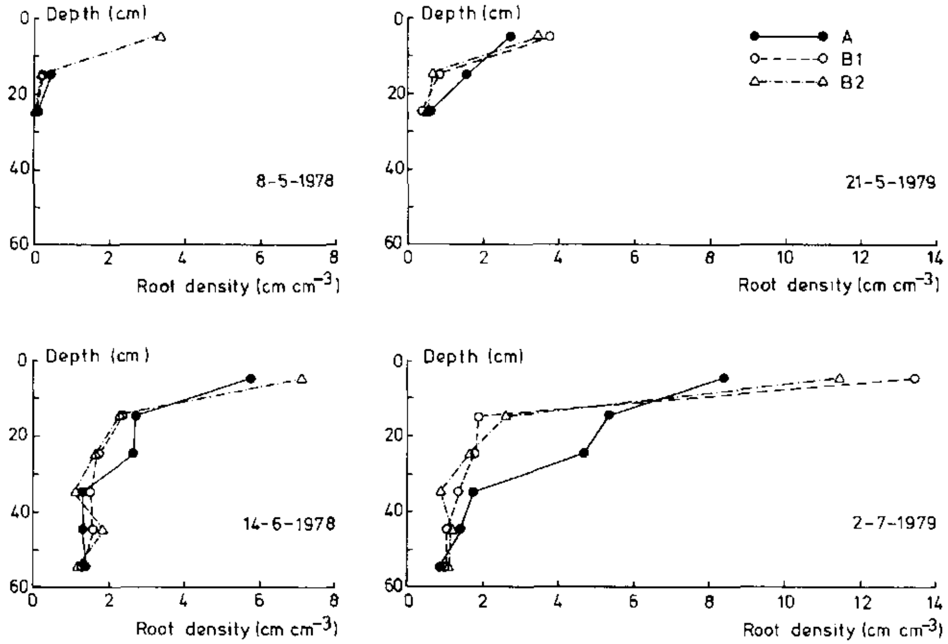


Fig. 57. Distribution of the root density determined from soil cores with depth in spring barley plots in 1978 and 1979.

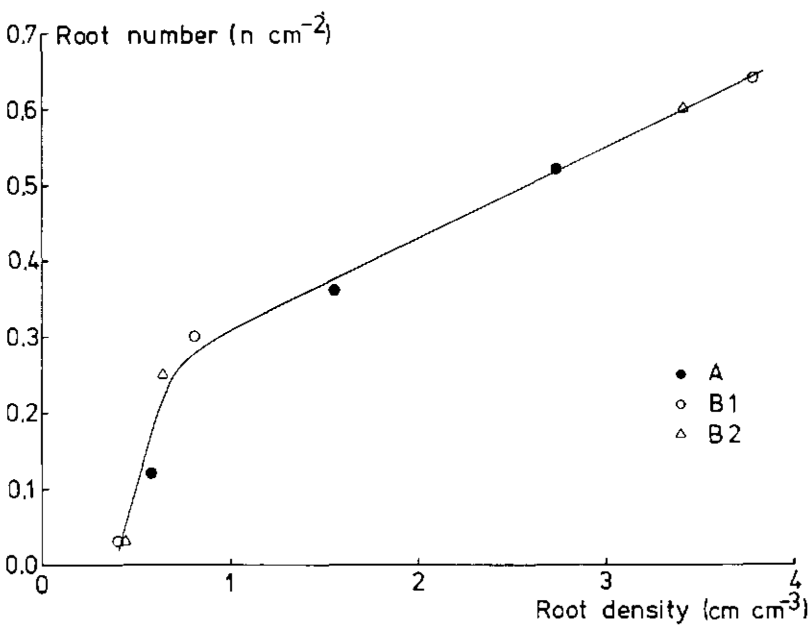


Fig. 58. Relationship between number of roots (n) counted on vertical profile walls and root density determined from soil cores (spring barley, 21 and 22 May 1979).

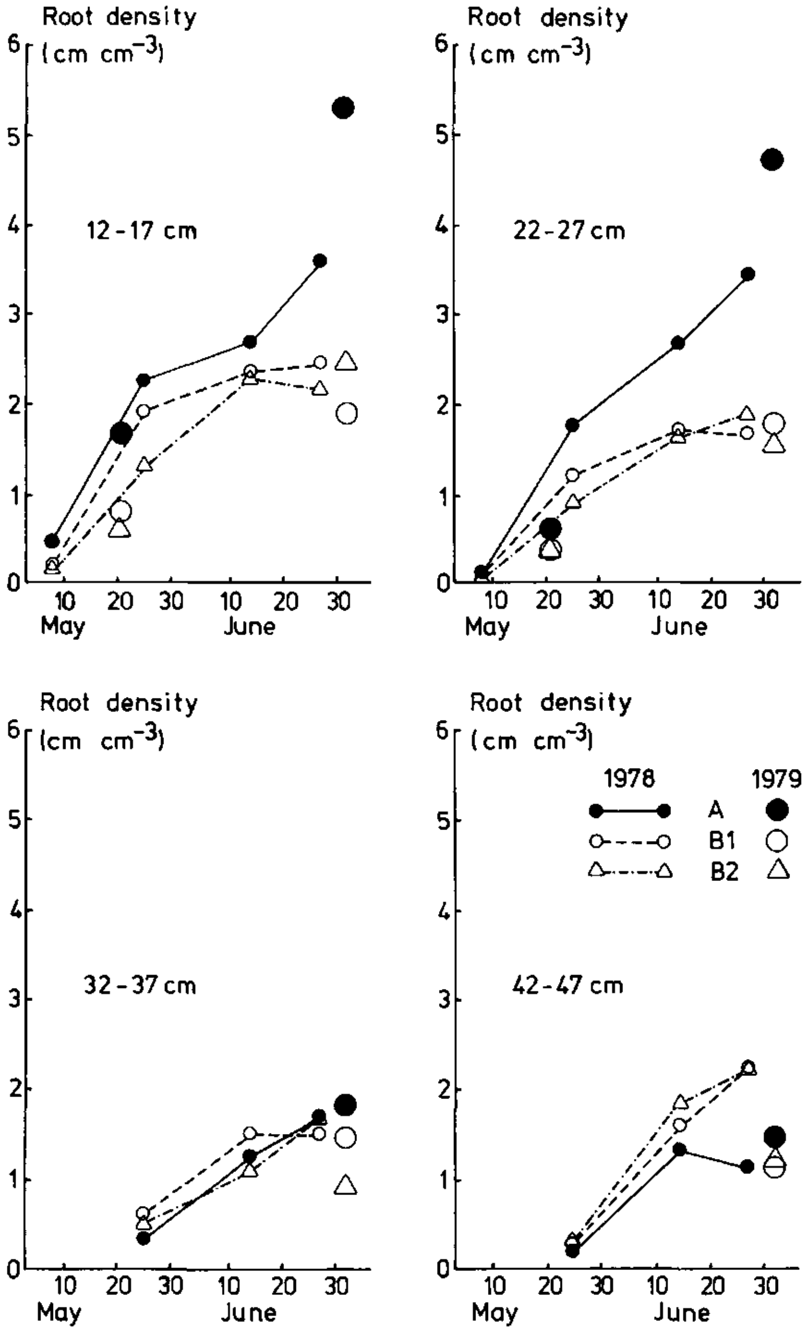


Fig. 59. Development of root density of spring barley with time in several characteristic soil layers in 1978 and 1979.

ploughpan. In System A, after mid-June, root growth below the ploughpan apparently stopped. In the wet 1979 growing season, root penetration and development in the ploughpan of Systems B1 and B2 were more hampered than in 1978. This resulted in a lower root density than in System A. The same was true for the soil just below the ploughpan but deeper in the soil the reverse was observed.

At the end of May 1979 the number of roots mid-way between plant rows was much smaller than within plant rows (Fig. 60). Mid-way between plant rows the arable layer of System B2 had a smaller number of roots than both other systems with a seedbed. By mid-June, when these differences had more or less faded away, another phenomenon was observed. Only mid-way between plant rows many roots had accumulated above the transition from the loose ploughed soil to the dense ploughpan. In System A, many roots had apparently failed to penetrate the ploughpan. As a result, below a depth of 40 cm fewer roots were found in the middle between than within the rows.

For the 1978 growing season, the increase in root density per day was plotted against cone resistance. Soil aeration was always adequate in the periods studied. It is clear that an increasing cone resistance diminished root growth strongly (Fig. 61). However, different relations are found for the tilled and untilled arable layer. Root growth in tilled soil probably stopped at a cone resistance of 3 MPa, whereas root growth rate in untilled

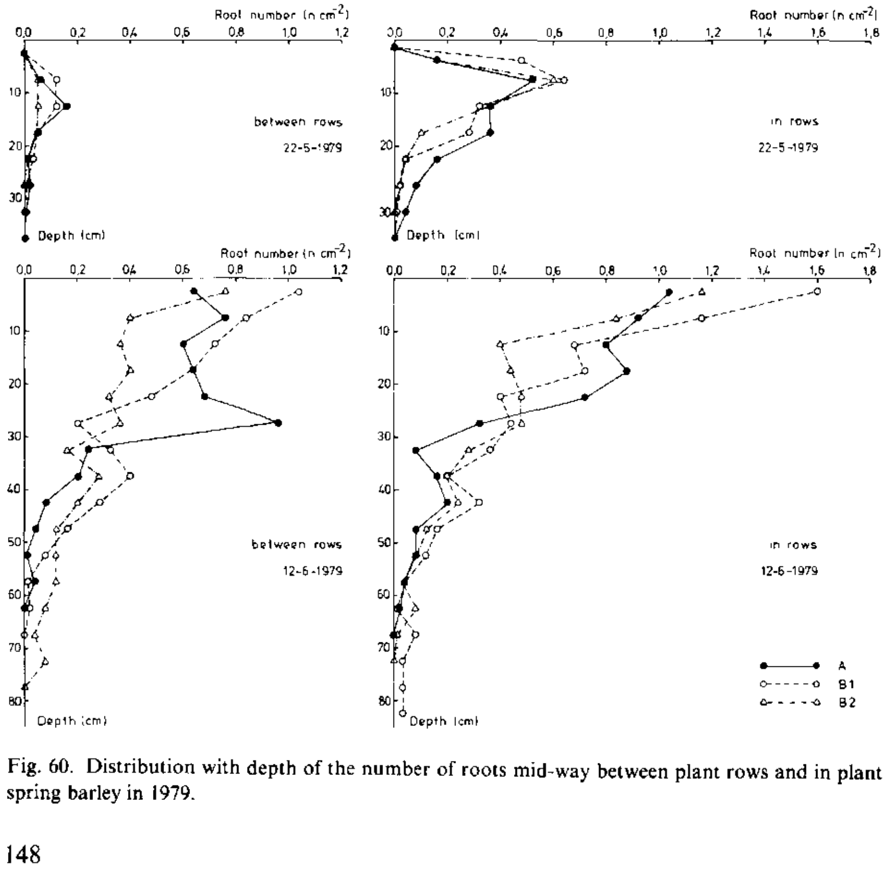


Fig. 60. Distribution with depth of the number of roots mid-way between plant rows and in plant rows of spring barley in 1979.

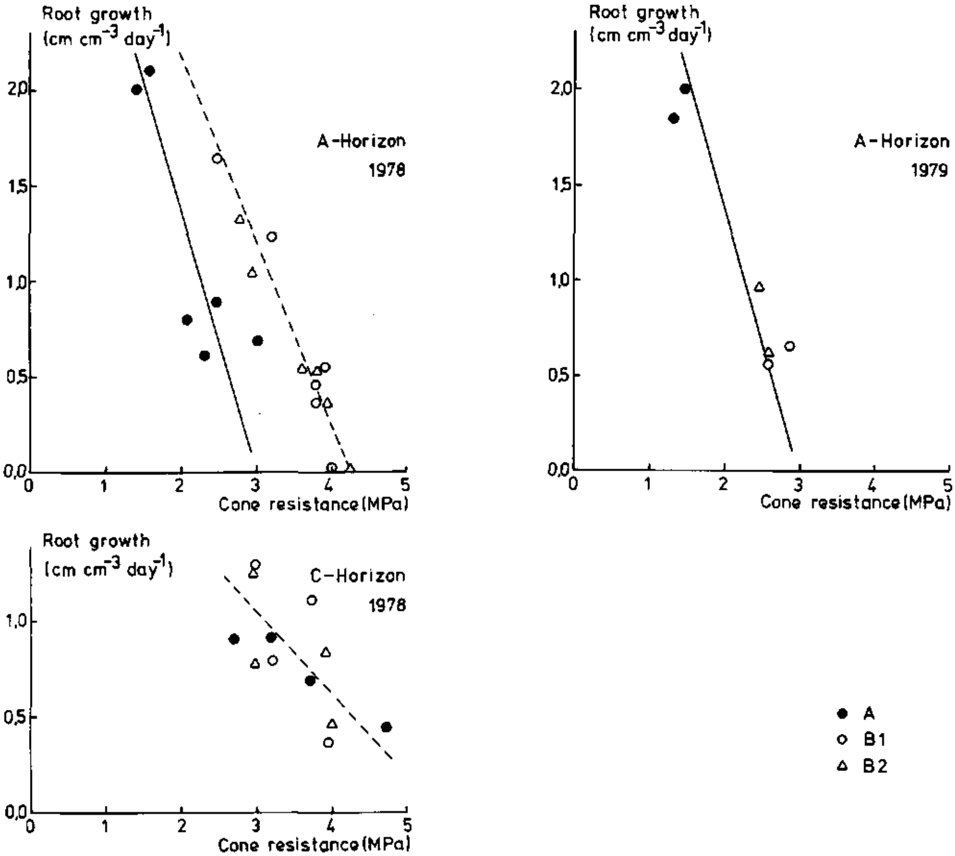


Fig. 61. Relationship between root growth and penetration resistance in spring barley plots in 1978 and 1979.

soil was still high at this resistance and did not stop until 4 MPa.

In 1979 a different picture was obtained. The period studied included the previously described second and third wet periods, which caused a temporarily insufficient aeration in untilled soil. Now the data of all systems closely followed the relation for the 1978 tilled soil. This means that in 1979 root growth in untilled soil was smaller at the same cone resistance than in 1978. Obviously root proliferation in untilled soil was much slower than tilled soil, not only because mechanical resistance was higher but also because aeration was temporarily insufficient. This conclusion is also supported by an estimation of root growth before the first measurement of root density. When the rooting front reached the 12 - 17 cm and 22 - 27 cm layers, soil aeration was already sufficient (Fig. 62) and stayed sufficient until the second wet period. Fortuitously, mean soil water content in this period and in the period that included the second and third wet periods were similar within a half percent by weight. Therefore, it can be assumed that mean cone resistances were also similar. Estimated daily increases in root density in untilled soil in the first period were more than 1.5 times as high as in the second period.

Because the period between root density measurements also included some time with a

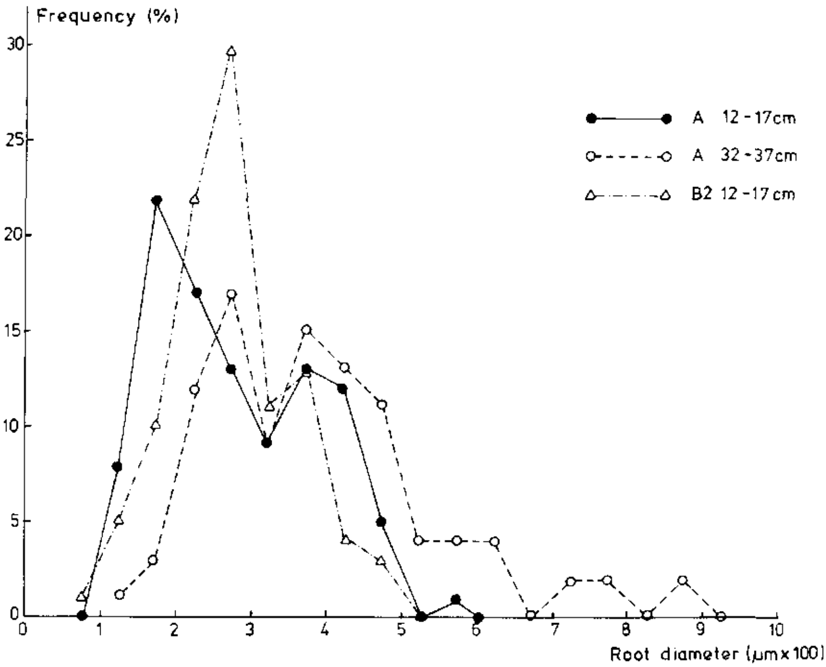


Fig. 62. Frequency of specified diameters of the root system of spring barley (mid-June 1978).

sufficient soil aeration, it may be concluded that insufficient aeration temporarily decreased root growth considerably. Nevertheless, these wet periods were not detrimental for the spring barley root systems. The combined effects of mechanical resistance and aeration had as a result that at the end of June – beginning of July root densities in the untilled arable layer were comparable in both years. In the ploughed soil, root densities were clearly higher in 1979 than in 1978.

Root diameters were measured when the soil had dried out, in mid-June 1978, to get information about possible changes in root morphology due to a high mechanical resistance. It appeared (Fig. 62) that mean root diameter of all roots grown in the 12 - 17 cm layer was similar in Systems A and B2: 281 μm and 283 μm, respectively. Many main roots in both systems had diameters of about 400 μm, but the number of these roots was smaller in System B2 than in System A. However, most first order laterals were clearly thicker in System B2 than in System A (mean diameters of 275 and 175 μm, respectively). Mean diameter of all roots grown in the ploughpan (32 - 37 cm layer) of System A was 399 μm, which is far more than in the arable layer. Most main roots had diameters around 400 μm, but quite a few were clearly thickened. Some main roots even had diameters of more than 800 μm. First-order laterals were as thick as those in the untilled arable layer.

8.3.7 Shoot growth

Shoot growth in 1979 started at a lower rate than in 1978 (Fig. 63), which was related

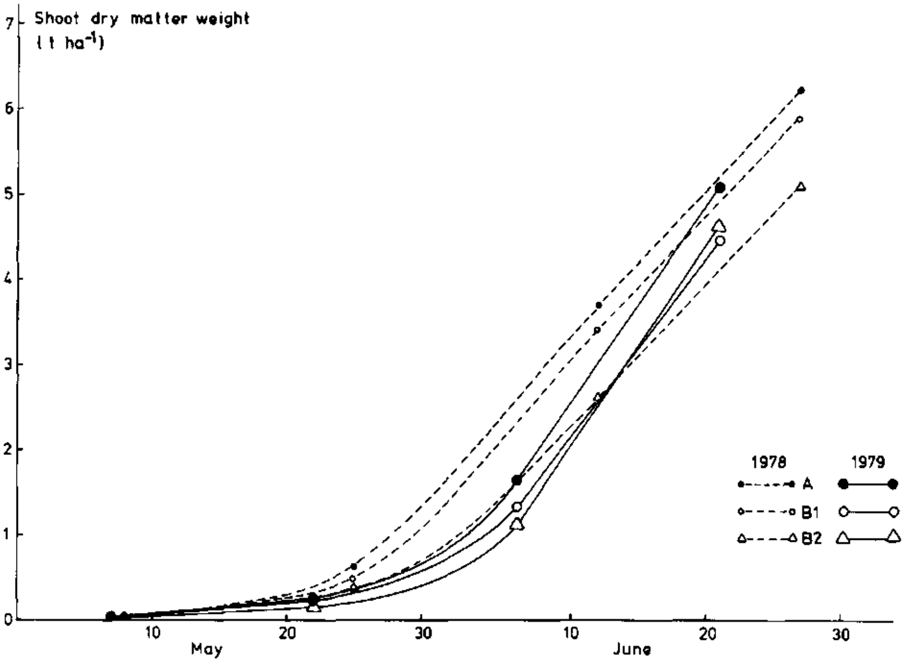


Fig. 63. Shoot growth of spring barley in 1978 and 1979.

to a higher rainfall and a lower evapotranspiration in May (Table 77). At the end of May – beginning of June 1979, rainfall was abundant and the spring barley crop in all systems, but especially on Systems B1 and B2, showed a temporarily yellowing of the leaves. Obviously this delayed crop growth. However, although potential evaporation was lower, crop growth thereafter accelerated and was even faster than in 1978. Because soil water content and therefore soil water potential was higher, it may be concluded that the rapid shoot growth in June 1979 was due to a greater availability of water to the plant roots.

About one week after emergence, shoot dry weight per hectare in System B1 was slightly smaller and in System B2 clearly smaller than in System A (Fig. 64). These

Table 77. Rainfall (R) and Potential Evaporation (E_0) in different periods.

1978			1979		
Period	R (mm)	E_0 (mm)	Period	R (mm)	E_0 (mm)
1/5 – 29/5	56	81	30/4 – 28/5	87	67
29/5 – 19/6	27	91	28/5 – 18/6	104	61
19/6 – 21/8	164	174	18/6 – 20/8	90	183
1/5 – 21/8	247	346	30/4 – 20/8	281	311

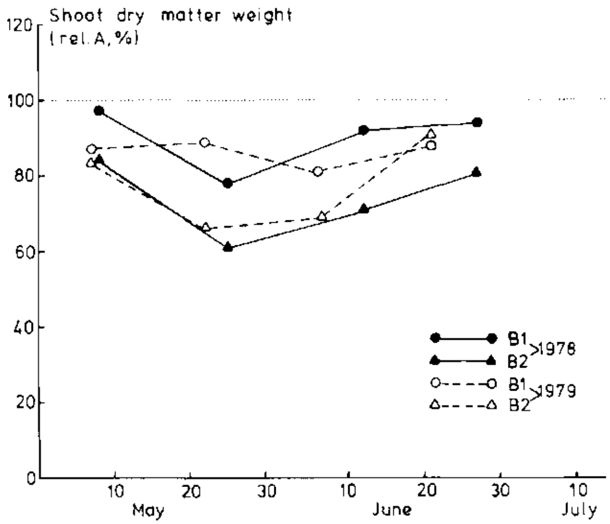


Fig. 64. Shoot dry matter weight of spring barley in Systems B1 and B2 relative to System A in 1978 and 1979.

differences can be explained to a large extent by differences in plant number. Shoot weight per plant in System B2 was only somewhat smaller, and in System B1 similar or even somewhat larger than in System A (Table 78). Therefore it may be concluded that, plants that had been established started to grow in about the same way. Obviously even plants grown without a seedbed (System B2) were hindered only to a minor degree by a rainy period around emergence.

However, in the weeks following, plant growth in untilled soil and especially in System B2, gradually stayed behind plant growth in System A. Relative differences in shoot dry weight were largest at the end of May-beginning of June. There was a tendency that these differences were somewhat larger and more rapidly attained in 1978 than in 1979. Minimum relative values in 1978 were 78% for System B1 and 61% for System B2. In the first part of June, because dry matter production increased very sharply, absolute differences in shoot weight between systems considerably increased. In 1978, nevertheless, differences in shoot weight between Systems A and B1 remained quite small, which coincided with a relatively small difference in root density in the arable layer. In the second part of June of both years, however, differences in shoot weight increased to a much smaller extent, which means that plant growth was nearly similar in all systems (Fig. 65).

Table 78. Shoot weight per plant relative (%) to System A.

1979 Fresh weight				1978 Dry weight				1979 Dry weight			
date	A	B1	B2	date	A	B1	B2	date	A	B1	B2
7/5	100	107	97	8/5	100	107	91	7/5	100	98	95
22/5	100	76	68	25/5	100	85	67	22/5	100	83	74

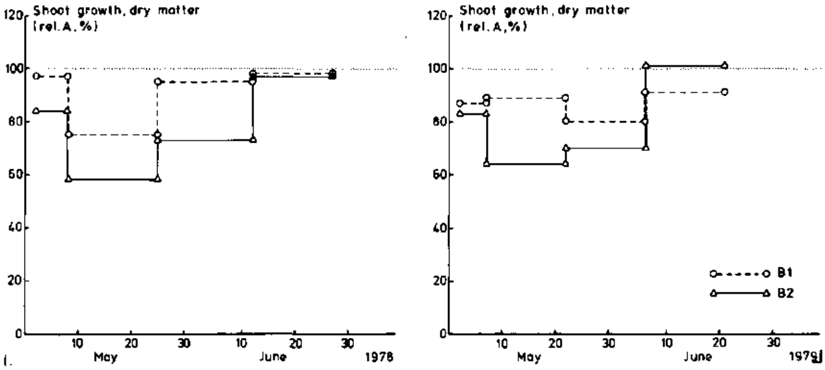


Fig. 65 Increase in shoot dry matter of spring barley in Systems B1 and B2 relative to System A in several periods of 1978 and 1979.

Dry matter percentages, measured on two occasions in 1978, were similar in all systems. In May and beginning of June 1979 values were about 1% lower in System A than in System B2. In this year differences in shoot fresh weight were therefore somewhat larger than in shoot dry weight. Plant development was also clearly slower in System B2 than in System A. This is indicated, for instance, by the percentage of plants in the tillering phase mid-June 1979: 59, 49 and 34% in Systems A, B1 and B2, respectively.

Shoot growth at different nitrogen applications was measured at two dates in 1979. One month after emergence the effect was still weak and mainly for applications of 0 – 40 kg ha^{-1} (Fig. 66). The relative increase in shoot dry matter for applications of 0 - 80 kg ha^{-1} was 55% for System A and 34% for System B2. Shoot weight per plant was quite similar in Systems A and B1 and, especially at the higher nitrogen applications, clearly smaller in System B2. Two months after emergence differences in shoot weight between different nitrogen applications had increased considerably. The relative increase in shoot dry matter for nitrogen applications of 0 – 80 kg ha^{-1} was 66% for System A and 53% for System B2. During the second month, especially in System B2, the response to nitrogen had increased. Shoot growth in this period in System B2 was very fast, which is also reflected in a somewhat lower dry matter content.

In 1978, plants in System B1 tillered somewhat more than in System A, which resulted in a nearly equal number of haulms per surface area (Table 79). At the end of June the weights per haulm were also nearly equal in these systems. Plants in System B2 did not tiller any more than System A and therefore the number of haulms per surface area was clearly lower than in System A. At the end of June the weight per haulm was also somewhat smaller than in System A.

In 1979, plants tillered more in System B1 and only somewhat more in System B2 than in System A (Table 80). However, in System B1 fertility of these extra haulms was smaller than in System B2. As a result the number of ear-bearing haulms per surface area was clearly smaller in both Systems B1 and B2 than in System A. Nitrogen fertilization, especially applications of 0 - 40 kg ha^{-1}, clearly increased the number of ear-bearing haulms per surface area in all systems (Fig. 67). This was accompanied by a minor decrease in dry weight per ear. The smaller number of ears in untilled soil was already at

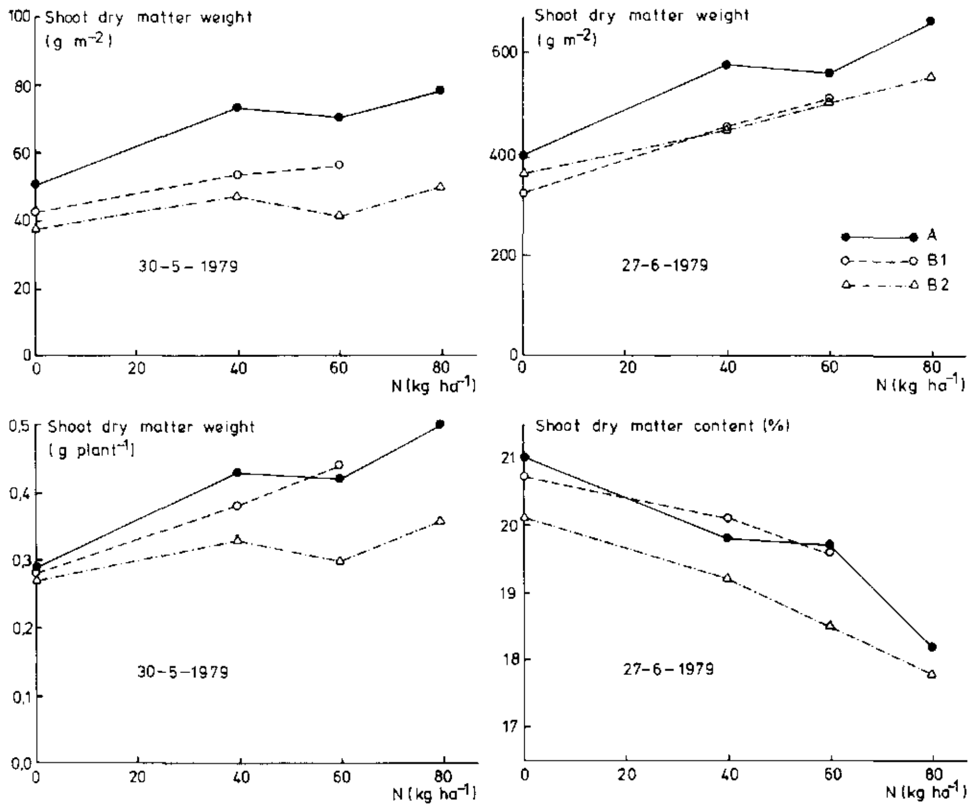


Fig. 66. Effect of nitrogen application on shoot dry matter weight and shoot dry matter content of spring barley at two dates in 1979.

the end of July partly compensated by a larger weight per ear (Table 80). Compensation increased with time. Ear weight per surface area in System B2 relative to System A increased from 80% on 26 July to 94% on 3 August, 19 days before the crop was harvested.

In view of the observed compensation effects, it is not surprising that in both years maximum grain yields were similar in all systems (Table 81). To obtain maximum yields,

Table 79. Number of plants and haulms m^{-2} and dry weight per haulm at 27 June 1978.

	Plant m^{-2}		Haulms m^{-2}		Haulms $plant^{-1}$		Dry weight $haulm^{-1}$	
	number	rel.	number	rel.	number	rel.	grams	rel.
A	135	100	586	100	4.34	100	1.063	100
B1	123	91	565	96	4.59	106	1.040	98
B2	123	91	518	88	4.21	97	0.976	92

Table 80. Number of plants and haulms m ^{2} and dry weight per ear at 26 July 1979.

	Plants m ^{2}		Haulms m $^{-2}$					Haulms plant ^{1}				Dry weight ear ^{1}	
	number	rel.	total		with ear		without ear	total		with ear		mg	rel.
			number	rel.	number	rel.	number	number	rel.	number	rel.		
A	172	100	805	100	796	100	9	4.68	100	4.63	100	682	100
B1	144	84	742	92	670	84	72	5.15	110	4.65	100	733	108
B2	136	79	667	83	655	82	12	4.90	105	4.82	104	736	108

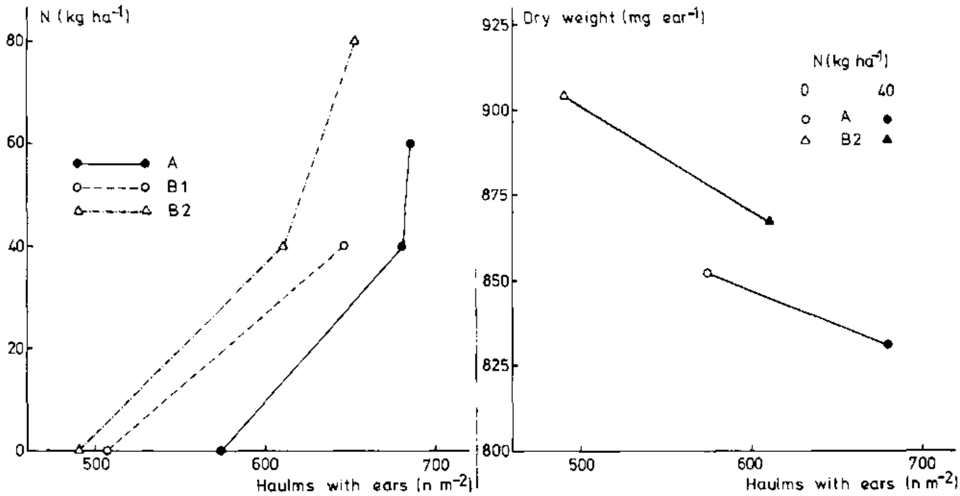


Fig. 67. Effect of nitrogen application on the number of haulms with ears and the effect of the number of haulms with ears on ear weight of spring barley (3 August 1979).

Table 81. Grain yield (t ha^{-1}; moisture content at 16% (w/w)) in spring barley at three perennial nitrogen levels in 1978 and 1979.

System	1978			1979		
	P−	P	P+	P−	P	P+
A	5.1	5.1	4.6	5.7	5.7	5.3
B1	5.2	5.2	5.1	5.5	5.5	5.6
B2	4.6	5.1	5.1	5.2	5.4	5.6

untilled soil, and especially System B2, needed a little more nitrogen than the ploughed soil of System A. In 1979 the yield level was somewhat higher than in 1978, which may be due to a better availability of water in June during vegetative growth, and more favourable conditions during flowering and grain-filling.

8.4 Discusssion

Tillage had a clear effect on soil conditions at seedbed preparation and sowing. In untilled soil, soil water content in the top few centimetres was higher than in tilled soil, owing to a greater capillarity and higher organic matter content. Therefore, under unfavourable conditions sowing time can be delayed. In 1978 and 1979, to facilitate the comparison of crop response, the spring barley crop was sown on the same day in all systems. Seedbed preparation with a powered rotary harrow resulted, therefore, in a coarser seedbed in the untilled soil of System B1 than in the ploughed soil of System A. In System B2, the triple-disc drill rather smeared the walls of the seed slits.

Because seeds are placed very close to the soil surface, the physical environment of the soil around the seeds is influenced to a large extent by the weather conditions. Nevertheless, seedbed characteristics and placement of the seeds, are important modifying factors. In System B2, not all seeds in the seed furrow were covered by aggregates, nor were they in close contact with the walls of the slit and, moreover, the slit was not always properly closed. This increases the chance that in a rainless period the soil around the seeds dries out more quickly than in System A, where several layers of aggregates above the seeds act as an evaporation barrier. A coarse seedbed, as found in System B1, can also be disadvantageous because sowing depth is more variable and the seed – soil contact is worse than in a fine seedbed.

Differences between systems became obvious during wet periods. Water infiltrated easily in the seedbed and ploughed soil of System A. In System B1 superficial slaking occurred, probably because water infiltration into the very dense soil below the seedbed was relatively slow. Therefore, runoff to small dips occurred in places. These small dips were already present at the start of the experiment. In System B1, however, they were aggravated at seedbed preparation for potatoes with the rotavator. After heavy rainfall the situation was even worse in System B2. Runoff from the slaked surface started earlier than in System B1, and water easily accumulated in the seed slits. In part of the seed slits, located in small dips, water was standing for several days, because water infiltration into smeared slits is very slow. The period during which aeration of the seeds was insufficient varied from place to place depending on seed placement in the seed furrow, degree of smearing of the slits and soil microrelief.

From this combination of measurements and observations it is understandable that final emergence in System B1 was somewhat lower (1978: 7%; 1979: 15%) and in System B2 clearly lower (1978: 24%; 1979: 34%) than in System A.

When this marine loam soil was not tilled, mean pore space gradually decreased for several years (Chapter 3). During compaction the weakest spots, which are usually the places with the largest pore space and largest pores, will be compacted first. As a consequence, soil structural heterogeneity decreases. It is therefore understandable that, except at soil water potentials close to zero, the volumetric water content is higher in untilled than in tilled soil. In the untilled soil of this experiment, this point was reached at a soil water potential of −5 kPa, i.e. the range of pores $>$100 μm. In the first instance, the hydraulic conductivity is related to the number of water conducting pores per surface area (Boone et al., 1978). Therefore, in untilled soil, it can be expected that at soil water potentials more negative than −5 kPa, hydraulic conductivity will be greater, but at soil water potentials less negative than −5 kPa, hydraulic conductivity will be smaller than in tilled soil.

The saturated hydraulic conductivity of untilled soil was about half that of ploughed soil. Nevertheless, the untilled soil still conducted at least 10 mm h^{-1}. This implies that only prolonged rainfall of a high intensity, which under Dutch circumstances is rare, would result in temporary waterlogging of untilled soil. However, especially in 1979, on a few occasions in spring, runoff and waterlogging in dips was observed. Apparently, impeded infiltration of water into the already slaked surface of untilled soil was the bottleneck (Bouma, 1977). Also the seedbed of the untilled soil of System B1 slaked slightly. This may be caused by an increased vulnerability to raindrop impact due to a temporary higher water content than the seedbed of ploughed soil. The saturated hydraulic conductivity of the ploughpan, including the transition from ploughed soil to the ploughpan, was about the same as the hydraulic conductivity of the untilled arable layer. In the porous spongy structure below the ploughpan the saturated hydraulic conductivity was about the same as in ploughed soil. Under the conditions of a Dutch growing season, therefore, in the whole soil profile, no serious problems such as perched groundwater tables may be expected. This was confirmed by all other field measurements. For instance, groundwater table depths were similar in both tilled and untilled soil. As long as there were no large differences in root density and subsequent water uptake, soil water potentials were also similar in both tilled and untilled soil. Although there may have been differences in soil water potential between systems on shorter terms than the actual measuring intervals, they apparently had no large impact on root and shoot behaviour.

The amount of oxygen available to the root system at a certain depth depends on both macro- and micro-transport of oxygen. Macro-transport from the surface to a certain depth occurs by diffusion through the air-filled pore system and is determined by the gas diffusion coefficient. The soil oxygen concentration depends on the supply of oxygen on the one hand and the demand of oxygen determined by the respiration of the root system and the soil microbes on the other. Micro-transport occurs over small distances from the nearest air-filled pores through the soil-water complex to the root surface. This process is simulated by a small, thin, negatively-charged platinum electrode, which reduces the oxygen at its surface at a rate (Oxygen Diffusion Rate, O.D.R.) determined by both the soil-water complex and the oxygen concentration at the interface between air and soil-water.

Aeration levels in the tilled and untilled soil of this experiment were significantly different. At the same soil water potential, air contents were considerably smaller in untilled soil. This was also true for the gas diffusion coefficients, although, at high soil water potentials, gas diffusion coefficients in untilled soil were somewhat higher than was expected from the small air contents (Chapter 3). When air contents increased, gas diffusion coefficients increased considerably and, therefore, differences in oxygen concentration with tilled soil diminished clearly. At intermediate high soil water contents, oxygen concentrations in untilled soil were even high. However, when the arable layer was close to field capacity (-10 kPa), and prolonged or heavy rainfall followed, soil aeration stayed still sufficient in ploughed soil but temporarily became insufficient in untilled soil. In both years, such wet conditions occurred around shoot emergence. At that time the gas diffusion coefficient was small but so was the oxygen consumption because soil temperature was low and the amount of roots in the surface layers still very limited. In untilled soil, therefore, the mean oxygen concentration decreased not so sharply, but the mean O.D.R. decreased to values that are assumed to be insufficient for root growth (Letey & Stolzy, 1964). Because evapotranspiration was still low, mean O.D.R. remained low for some time in the most dense part of the untilled arable layer. Nevertheless, root growth to depth in the arable layer was similar in both tilled and untilled soil.

In the 1978 and 1979 growing season, after shoot emergence, soil conditions with respect to aeration were different. During May and June 1978, there was clearly less rain than in 1979. In 1978, insufficient aeration cannot explain differences between systems in root growth in the arable layer. In untilled soil, mechanical resistance was the major physical factor reducing root growth. In 1979 both mechanical resistance and temporarily insufficient aeration were involved. In this year, the oxygen concentration in untilled soil temporary fell clearly below 10% (v/v). During the second wet period of 1979, when soil water content was higher and evapotranspiration lower, oxygen concentrations and O.D.R. were low for a longer time than during the third wet period.

It was shown that it can be expected that in the ploughed arable layer the O.D.R. will be insufficient only at very high soil water potentials, close to saturation. In untilled soil, insufficient O.D.R. already occurred at soil water potentials between -2 and -3 kPa as occur during prolonged rainfall in spring. In the ploughpan of System A, which had a slightly worse soil structure than the ploughpan of Systems B1 and B2, this even occurred at soil water potentials somewhat more negative than -5 kPa. In spring, the ploughpan and deeper soil layers of all systems had an insufficient O.D.R. for a long time during and after wet periods. Under these conditions there was a sharp contrast in aeration between the ploughed soil and soil layers deeper in the soil profile. In 1978, soil water content in the lower part of the arable layer of System A decreased slightly due to uptake of water by the fast growing root system, and therefore the aeration of the ploughpan improved more rapidly than in the ploughpan of Systems B1 and B2. In contrast, in 1979 the soil in or just below the ploughpan of System A had a low O.D.R. up till the end of the third wet period. In these layers in both other systems soil structure was somewhat better, and between part of the previously mentioned very wet periods aeration was sufficient.

Cone resistances were much higher and more variable with water content in untilled soil than in ploughed soil. Typical values at soil water contents close to field capacity were 2 – 3 MPa for untilled and 1 – 1.5 MPa for ploughed soil. Values at ploughpan depth were comparable with those in the untilled arable layer at similar water contents, but they were always slightly higher in System A than in Systems B1 and B2. When the soil dried out the 3 and 4 MPa levels were also passed earlier in the ploughpan of System A than in both other systems. This was explained by the somewhat more strongly developed ploughpan in System A and by the higher root density, which resulted in a higher water uptake from the soil just above the ploughpan.

During both years, root growth to depth occurred at soil water potentials close to field capacity. However, root proliferation and branching within the different soil layers occurred under different conditions. In 1978, soil water contents decreased early in the season and, therefore, during root development cone resistance in the untilled soil increased sharply to values >4 MPa. In 1979, on the contrary, soil water contents remained high for a long period and root development proceeded at intermediate cone resistances for more than one month.

Between tillage systems, many aspects of root growth were different. However, there was one important exception. In the arable layer the expansion of the rooting front was fast and similar in all systems. This occurred in spite of more adverse soil conditions and especially a larger cone resistance in the untilled soil. This points to an important aspect of the soil structure of the untilled soil. Although a large number of the largest pores disappeared by compaction, nevertheless many pores with dimensions equal or larger than the primary roots of spring barley, were remained. Gas diffusion coefficients at low air contents were even somewhat higher on the untilled than on the tilled soil (Chapter 3), which points to a greater continuity of these pores. Therefore the fast expansion of the rooting front in untilled soil can be explained when it is assumed that the first roots followed the paths of least resistance, i.e. the remaining large pores and fissures with a good continuity. Perhaps also planes of weakness, developed by shrinking and swelling processes contributed to the observed phenomenon. This assumption is supported by the fact that the mean diameter of the primary roots was not greater in untilled soil than in tilled soil.

Soil structure changed tremendously at the transition from the loose ploughed soil to the dense ploughpan. It can be expected that in the soil that has not been tilled for 8 years pore continuity at this transition will be greater (Goss et al., 1982). In 1978 the impression was obtained that the first roots had passed this transition more easily in Systems B1 and B2 than in System A. However, greater depths in the C horizon were reached at about the same date in all systems. Moreover, in 1979 in all systems roots were hampered in a comparable way as in 1978 in System A. Aeration cannot explain these differences because in the ploughpan of System A the O.D.R. was sufficient in 1978 but insufficient in 1979. In these years in both other systems aeration was insufficient or hardly sufficient. Therefore, it can be concluded that, with respect to root growth, during eight years of no-tillage the soil structure of the ploughpan had not improved very much. This conclusion is supported by the fact that in all systems, once the roots had reached the undisturbed spongy structured subsoil, root growth to depth accelerated again. In 1979 this happened, although mean O.D.R. values pointed to an insufficient aeration. Therefore, it should be emphasized that in spongy soil structures with many vertical continuous medium sized pores, O.D.R. values have to be interpreted carefully. Aeration within these pores will be greater than in the more or less homogeneous soil between those pores! In Systems B1 and B2, root density below the ploughpan also increased faster and to a higher level than at ploughpan depth.

In the untilled soil the amount of roots in the arable layer decreased very sharply with depth whereas in ploughed soil the root distribution was more uniform. It is not likely that accumulation of nutrients in the surface layer and a diminished availability at greater depths (Chapter 5), was the main cause for this phenomenon. Research carried out with maize in homogenized soil revealed that, irrespective the level of nutrients, this phenomenon could be explained by a higher mechanical resistance (Boone & Veen, 1982). Probably the higher mechanical resistance was the principal factor, and an uneven distribution of nutrients or, in 1979, a temporarily insufficient aeration, which only strengthened this effect.

Root growth diminished strongly with increasing penetration resistance, but in a clearly different way in ploughed than in untilled soil. Root growth in the ploughed soil probably stopped at a penetration resistance of 3 MPa, which is in accordance with most literature (e.g. Taylor & Gardner, 1962). In untilled soil, root growth at this resistance was still rather strong and did not stop until a penetration resistance of 4 MPa was reached. Especially in untilled soil, roots encountered a clearly lower mechanical resistance than penetration resistance would suggest. This observation together with the fact that the dry, massive, untilled soil mass could be broken in sharp-edged aggregates (but sometimes even in the field at a friable condition) led to the following concept.

Probably the untilled soil was composed of a conglomerate of densely packed aggregates with small pores, which primarily determined penetration resistance, and of a sparse and more or less continuous system of medium sized and large pores. Roots easily grow in the part of the system with pore necks not smaller than the root diameter of spring barley. Provided the resistance of the soil mass is not too high, at spots with smaller pore necks, roots can slowly penetrate the least serious necks by widening them. Planes of weakness between the aggregates could also offer some possibilities for the root system. Concentrations of roots on aggregate surfaces have been observed many times. However, it is still likely that, due to insufficient pore continuity, a significant part of the pore system cannot be used by the root system. This implies that in untilled soil, the rootable pore system will be rather sparse. There is a real chance that part of the system will be used again by the root system of subsequent crops. This is supported by the observation that in some of the larger pores, living roots as well as decayed parts of the root system of a previous crop were found.

Lateral roots are clearly thinner than primary roots. Consequently, for unimpeded root growth smaller pores would suffice. However, these laterals develop at arbitrary places along the primary root axes. Therefore, for many of these laterals the chances are great that they will encounter a high mechanical resistance. In agreement with this hypothesis, measurements of root diameters revealed that when in untilled soil cone resistances had increased considerably, primary roots were hardly influenced but first order laterals had clearly thickened.

The second and third wet period of the 1979 growing season reduced the mechanical resistance in untilled soil. At the same time, aeration levels temporarily dropped below critical values. At the same penetration resistance root growth was therefore smaller than in 1978. A totally insufficient aeration has to be considered as the primary factor that stopped root growth and ion uptake during these short periods when the soil was nearly waterlogged. Temporary yellowing of the leaves of spring barley, in untilled soil more than in tilled soil, was a clear symptom. In untilled soil at slightly decreased soil water potentials, aeration was still insufficient at many spots. In this situation both mechanical resistance and insufficient aeration diminished root growth. In the previously described model of the pore system, a variable proportion of a root system is surrounded by a saturated (or almost saturated) soil-water complex. This proportion varies with soil water potential and increases at less negative water potentials. These soil-water complexes, occurring especially at places with narrow pores or pore necks, are almost impermeable for oxygen. The maximum mechanical pressure the root can exert will be diminished when the expanding root tip has to deal with a shortage of oxygen (Gill, 1956). In 1979, when the insufficient aeration had no permanent detrimental effects on spring barley, evapotranspiration decreased soil water content and improved aeration rapidly. At the same time soil mechanical resistance was increased. It is therefore not surprising that in 1979 the ultimate result was, that at the end of June – beginning of July root densities in the untilled arable layer were comparable with those found in 1978.

In a homogeneous soil (physical) environment, every spot has the same rootability. In a heterogeneous soil (physical) environment, rootability depends on the spot concerned. The absolute differences in rootability between different spots as well as the dimensions of these spots determine the degree of heterogeneity in rootability. Under similar conditions actual differences in root growth between different spots are, however, seasons, the ploughpan, too, formed no serious barrier for water transport.

4. When the soil was at field capacity (–10 kPa) aeration in the arable layer was sufficient (mean O.D.R. >20 10^{-8} g cm $^{-2}$ min $^{-1}$) in both tilled and untilled soil. At soil water potentials less negative than about –3 kPa, which were observed in spring for some time during prolonged or heavy rainfall, aeration was still sufficient in the ploughed soil but insufficient in the untilled soil.

5. In 1978, aeration in the tilled and untilled arable layer was sufficient and observed differences in root growth of spring barley between tillage systems must be ascribed to differences in soil mechanical resistance. In 1979, due to a much higher amount of rain in May and June, differences in both mechanical resistance and aeration were responsible for differences in root growth of spring barley between tillage systems.

6. The oxygen diffusion rate (O.D.R.) of ploughed soil was low only when the soil was nearly saturated. In general, the poorer soil structure the more negative the soil water potential had to be to obtain a sufficient O.D.R. In the wet 1979 growing season, in plots with spring barley, these values were reached somewhat later in the ploughpan of the loose-soil husbandry than in the ploughpan of both the no-tillage systems.

7. The expansion of the rooting front of spring barley in the arable layer occurred when the soil was at about field capacity and penetration resistance amounted to 2 – 3 MPa and 1 – 1.5 MPa in untilled and tilled soil, respectively. Root proliferation and branching occurred in 1978 at lower water contents and, therefore, in untilled soil at sharply increased cone resistances. In 1979, on the contrary, soil water contents remained high for more than one month and, thus, root development proceeded at intermediate high penetration resistances.

8. The penetrometer resistance of the ploughpan was always somewhat higher in loose-soil husbandry than in both no-tillage systems, because in loose-soil husbandry the ploughpan was slightly stronger. Moreover, in the early growing season, due to a higher root density of the spring barley crop in the lower part of the arable layer, soil water content of the ploughpan decreased somewhat earlier than in both no-tillage systems.

9. In the arable layer, root growth of spring barley to depth was fast and similar in tilled and untilled soil. In the ploughed soil, root growth stopped at a penetration resistance of, probably, 3 MPa. However, in 1978 in untilled soil root growth did not stop until penetration resistance reached 4 MPa. This fits into the concept that untilled soil was composed of a system of densely-packed aggregates, which primarily determined penetration resistance, and a sparse but more or less continuous system of pores with dimensions greater than or at least comparable with those of spring barley roots.

10. In 1979, soil water contents were quite often higher and cone resistances lower than in 1978. In untilled soil this had as a result that in 1979 both a temporary insufficient aeration and a still appreciable cone resistance diminished root growth as much as cone resistance alone did in 1978. As a consequence, in both years root densities in the untilled arable layer were similar.

11. In untilled soil the number of roots of spring barley in the arable layer decreased very sharply with depth, whereas in the ploughed soil root distribution was more uniform. This difference was primarily caused by differences in mechanical resistance. In the 1979 growing season it was shown that temporary insufficient aeration increased this effect.

12. During 8 years of no-tillage, the rootability of the ploughpan did not improve very

much. In all systems the ploughpan temporarily hampered root growth of spring barley to depth. The rootability was better in the subsoil than in the ploughpan.

13. Root growth of spring barley in the subsoil was slightly better under no-tillage than under ploughed soil. This is in accordance with the concept of preferential growth of roots, which implies that root growth in a certain soil layer is increased when the possibility for root growth in an other layer with growing roots is decreased.

14. Once established, spring barley plants started to grow at about the same rate in all systems. In untilled soil in which a seedbed was prepared, shoot growth of individual plants was initially even somewhat better than in ploughed soil. In the following weeks, however, in untilled soil, especially without a seedbed, shoot growth and development, both per area and per plant, lagged behind. These differences between systems are in accordance with differences in root growth.

15. In both 1978 and 1979, about one month after shoot emergence, differences in shoot dry weight of spring barley were maximal and quite large: in untilled soil without a seedbed, shoot dry weight was less than two-thirds of that in ploughed soil.

16. From the moment the root system in untilled soil had passed the ploughpan and started to exploit the subsoil, shoot growth rates of spring barley were about similar in all tillage systems.

17. On untilled soil, tillering only partly compensated for the lower plant density of spring barley. However, compensation progressed with time by increasing ear weight.

18. In both 1978 and 1979, grain yields of spring barley were similar in all tillage systems. However, untilled soil, especially when no seedbed was prepared, required slightly higher nitrogen fertilization rates than ploughed soil.

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9 Soil conditions and growth of sugar beet on a tilled and untilled marine loam soil

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9.1 Introduction

During the first crop rotation (1972 – 1975) it was found that yields of potatoes and especially sugar beet were considerably lower on untilled than on tilled soil. Therefore in 1978 and 1979 detailed study was made of the effects of tillage-induced changes in soil water, soil aeration and mechanical impedance on root and shoot growth of sugar beet. The research was carried out in the two tillage systems with the largest differences in soil structure, viz. System A (loose-soil husbandry) and System B1 (no-tillage with root crops).

9.2 Materials and methods

9.2.1 Introduction

In 1977 and 1978, to avoid problems in System B1 with seedbed preparation, sowing and emergence of sugar beet, the straw of the previous wheat crop was baled and removed. In System A the straw was chopped and spread. In all systems the undersown grass obtained nitrogen levels of 50 kg ha^{-1} to ensure a good development. At the end of October 1977 and in mid-November 1978, System A was ploughed to a depth of 25 cm under favourable soil conditions, and the ploughed surface was levelled by harrowing in the same pass. The wheat straw, stubble and grass green manure were well turned in. In System B1 the grass was killed off with glyphosate and, to improve soil drying and workability, some time before the expected date of seedbed preparation in spring, the soil was tilled superficially with a tooth harrow. As a result, in System B1 the topsoil dried to the extent that in both systems seedbed preparation and sowing could be performed on 17 April 1978 and 19 April 1979. In System A, seedbed preparation with a powered rotary harrow and cage roller, and sowing were combined into one pass. In System B1, seedbed preparation was very intensive with a full-width rotary cultivator; after sowing to improve the seed-soil contact and protect the seedbed from drying out, the field was rolled with a Cambridge roller. In both systems sowing depth was 2.5 cm, but as a precaution, in System B1 the distance in the row was smaller (7 cm in 1978 and 11 cm in 1979) than in System A (15.5 cm). In System B1 in the last week of May, the sugar beet were singled to a stand of 100 000 plants in 1978 and 98 000 plants in 1979; in System A singling was not needed. In System B1, nitrogen fertilizer was applied some time before seedbed preparation. In System A, in 1978 nitrogen fertilization was combined with seedbed preparation and sowing, but in 1979 nitrogen was applied at an earlier date when the soil was superficially frozen by nightfrost. In both years nearly all research was carried out on the subplots with the annual nitrogen level N3 (120 kg ha $^{-1}$) of repetition I, which is close to the normal amount of nitrogen used in agricultural practice in this region.

9.2.2 Meteorological data and soil physical determinations

For sugar beet the same methods were used as for spring barley (Subsection 8.2.2). However, in sugar beet plots saturated hydraulic conductivity was not determined.

9.2.3 Root and shoot growth

To determine root length, at different depths in the crop rows, intact soil cores (100 cm^3, 10 replicates) were taken. It appeared to be impossible, even when soil dispersing chemicals were applied to adequately separate the sugar beet roots from the soil without previous drying. Therefore the soil was dried at 50°C and washed out carefully over a fine sieve (0.3 mm openings) cleaned by hand and stored in alcohol (96%). However, upon drying sugar beet roots, in contrast with spring barley, turned yellow brown. This obstructed separation of living roots, dead roots and organic debris (especially in the surface layer of System B1 and in the layer above the ploughpan of System A). Unfortunately therefore, reliable quantitative root data from the 1978 experiment, determined as the number of intersections of living roots with the lines on a grid (Newman, 1966), are limited. In 1979, semi-quantitative root data were obtained from profile wall observations using the slightly modified method of Reymerink (1964).

During emergence the number of sugar beet that had emerged were counted in 6 rows of 10 m length. Shoot and taproot fresh and dry weights were determined in duplicate from subplots of 80 - 100 plants at several occasions during the growing season. In 1979, in addition to test the influence of nitrogen on these parameters, all 6 annual nitrogen levels were harvested at two dates. At the latter date also the sugar content and the amounts of K, Na and α-amino-N in the taproot were determined. In both years, taproot length, maximum taproot diameter, number of fanged taproots and degree of fanging were determined.

9.3 Results

9.3.1 Soil structure

In both Systems A and B1, a seedbed of about 3 cm deep was prepared. However, in System B1, due to the uneven surface (dips and ruts) and the shallow working depth of 3 m wide rotary cultivator, seedbed depth was very variable (1 – 4 cm). Consequently part of the core samples of the 2 – 7 cm layer of System B1 contained a part of the seedbed and, thus, a relative large pore space was found (Table 82). There was a very large change in soil structure from the loose seedbed to the very dense untilled soil underneath. The densest soil, with a small standard deviation was found at a depth of 12 - 17 cm. Water content at pF 2.0 was also lowest in this layer and air content at pF 2.0 was only about 4% compared with about 13% for the same soil layer of System A. In System A, the grass green manure, chopped winter wheat straw and stubbles were ploughed in to 25 cm

Table 82. Mean ($\bar{X}$)[a] and mean standard deviation ($\bar{S}$)[b] of pore space, water content at pF 2.0 and air content at pF 2.0 on sugar beet plots during the growing seasons of 1978 and 1979.

	Depth (cm)	System A		System B1	
		1978	1979	1978	1979
Pore space (%, v/v)					
$\bar{X}$	2 - 7	46.7	51.5	41.5	46.4
	12 - 17	46.6	48.1	39.3	39.7
	22 - 27	46.0	47.3	41.1	41.6
	32 - 37	39.0	39.7	40.5	45.3
$\bar{S}_x$	2 - 7	3.4	2.4	2.0	2.4
	12 - 17	4.6	3.9	1.8	1.5
	22 - 27	2.1	2.5	1.9	2.1
	32 - 37	1.1	1.1	1.1	0.8
Water content at pF 2.0 (%, w/w)					
$\bar{X}$	2 - 7	23.3	24.6	23.2	24.7
	12 - 17	23.9	24.9	21.7	22.4
	22 - 27	25.2	25.6	22.9	23.4
	32 - 37	22.0	22.3	23.6	27.5
$\bar{S}_x$	2 - 7	0.7	0.8	0.7	0.7
	12 - 17	2.3	1.8	0.8	0.8
	22 - 27	1.6	2.0	1.0	1.1
	32 - 37	0.5	0.7	0.7	0.8
Air content at pF 2.0 (%, v/v)					
$\bar{X}$	2 - 7	13.5	19.6	5.3	11.1
	12 - 17	12.5	13.6	4.1	3.6
	22 - 27	9.7	11.3	5.1	5.1
	32 - 37	3.0	3.5	2.7	4.8
$\bar{S}_x$	2 - 7	4.9	3.6	2.7	3.4
	12 - 17	5.4	5.1	1.7	1.5
	22 - 27	3.1	2.8	2.0	2.3
	32 - 37	1.3	0.9	1.1	1.6

a. n = 20.
b. n = 2.

depth. This resulted in a loose soil with a high standard deviation of pore space in the 12 - 17 cm layer and a relatively high water content at a soil water potential of - 10 kPa (pF 2.0) in the 22 - 27 cm layer.

Soil structure on System A changed tremendously from the loose ploughed soil to the very dense ploughpan. The 32 - 37 cm layer of the ploughpan of System A was even slightly denser and had a slightly lower water content at pF 2.0 than the corresponding layer of System B1. This difference in water content at pF 2.0 was significant in both years but this difference in pore space only in 1979. However, it can be doubted if these 1979 B1 values were representative, because pore space and water content at pF 2.0 were much higher than could be expected (see also Chapter 8). Air content at pF 2.0 at ploughpan depth of both systems was about 3% (v/v).

Below the ploughpan the soil had a porous spongy structure and pore space was considerably larger and showed only small variations with location and depth. Between

47 and 102 cm depth, mean pore space was 45.5% (v/v), water content at pF 2.0 25,4% (w/w) and air content at pF 2.0 8.2% (v/v). Standard deviation was very low.

9.3.2 Germination and emergence

In System B1, at seedbed preparation and sowing, soil water content of the top 3 cm was higher and the soil was more sticky than in System A (Fig. 68). Nevertheless, in 1978 the intensive seedbed preparation in System B1 and the far less intensive seedbed preparation in System A resulted in a rather fine seedbed in both systems (Chapter 4). In 1979, because soil water content was higher, the same seedbed preparation resulted in a coarser seedbed, especially in System B1. In System B1 most aggregates had more or less the same diameter, whereas the seedbed in System A was more heterogeneous. Mean seedbed depth was about 2.5 cm but, especially in System B1, quite variable from place to place due to dips and shallow ruts present at seedbed preparation.

In 1978, in the first 10 days after sowing there was only 3 mm of rain. In this period the top half of the seedbed of both systems dried out till a soil water potential more negative than -1.6 MPa (pF 4.2). In the lower part of the seedbed of System A, the soil water potential remained close to -50 kPa (pF 2.7). In System B1 values remained even somewhat less negative due to a better capillary transport from the dense soil to the seedbed. The soil water potentials of both systems were still high enough to guarantee rapid imbibition. In the next three days a little rain increased soil water potentials. Heavy rainfall one day later (1 May), slaked the surface of the seedbed in both systems. In System B1 runoff to dips resulted in temporary ponding at some places as was observed on 2 May. Probably for about 2 days, soil water potentials at sowing depth were clearly less negative than -10 kPa (pF 2.0). On 2 May the first sugar beet plants also emerged. Drying of the slaked surface after this rain was temporized by drownsy weather and, therefore, emergence was very rapid in the next few days (Fig. 69). Final emergence was good in both systems and even higher in System B1 (70%) than in System A (61%). Because sowing distance in the row was 15.5 and 7 cm in Systems A and B1, respectively, mean plant density was adequate in System A but far too high in System B1 (Table 83). Plant density in the row was more uniform in System B1 than in System A. Plant densities on the research plots were about the same as on other plots of the experimental field.

In 1979, contrary to 1978, after sowing there was rain every now and then. Therefore, in this year soil water content during germination was clearly higher than in 1978. In both systems the top half of the seedbed stayed moist and, during days without rainfall, soil water potentials at sowing depth were close to -10 kPa (pF 2). However, because temperature was lower, germination proceeded slower than in 1978. On 2 May, 13 days after sowing, heavy rainfall slaked the soil surface seriously, especially in System B1. The next few days were also rainy and, therefore, water was ponding for several days in the lower spots of System B1. On 7 May, one day after the last rain, the first sugar beet plants emerged. The slaked surface dried out rapidly and most plants counted on 9 May, especially in System B1 had emerged through fissures in the crust. Below the crust, buckling of the epicotyls of plants not yet emerged had been observed at several instances. Therefore, rainfall 2 and 3 days later, which weakened the soil crust must have been very favourable for emergence. Final emergence was 61 and 64% in Systems A and

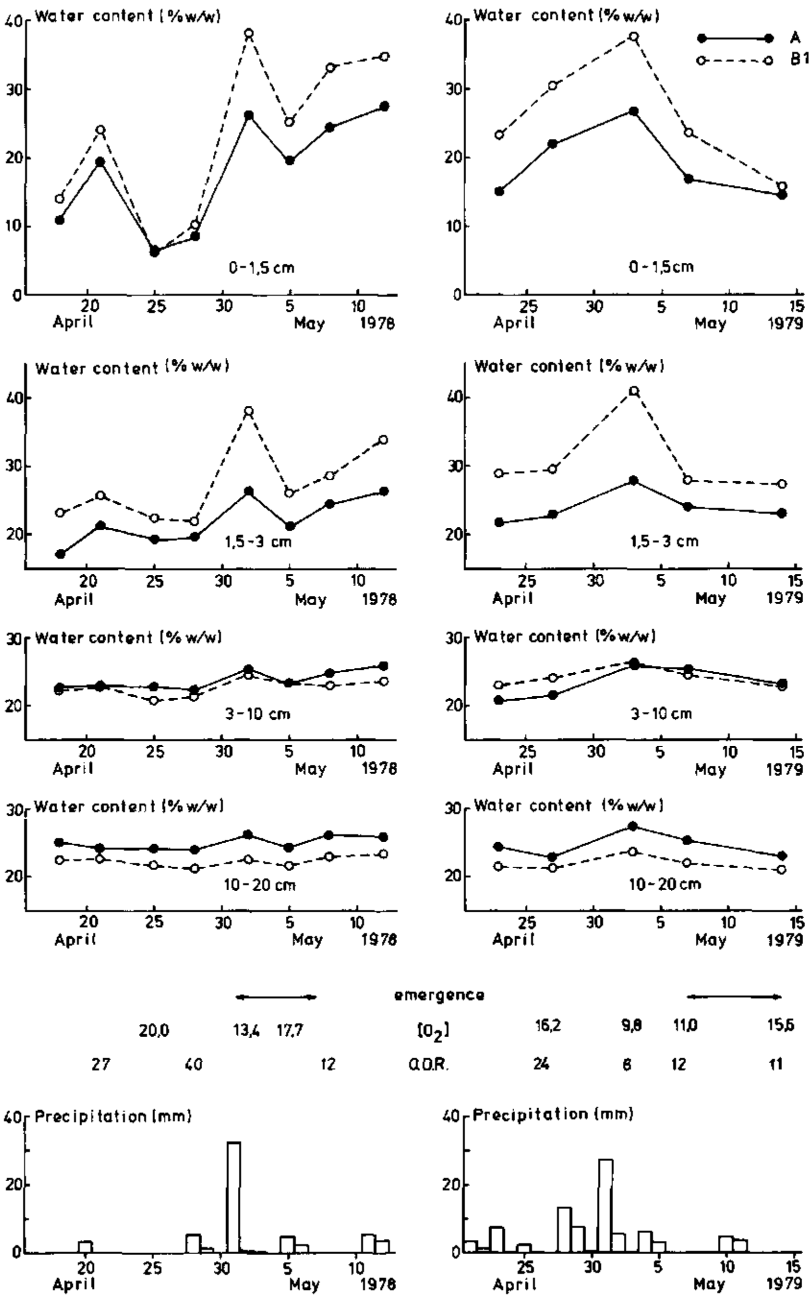

Fig. 68. Soil water content in and below the seedbed during germination and emergence of sugar beet. Bottom: period of emergence, oxygen concentration (O_2; %, v/v) and oxygen diffusion rate (O.D.R.; 10^{-8} g cm^{-2} min^{-1}) in untilled soil at 10 cm depth and precipitation.

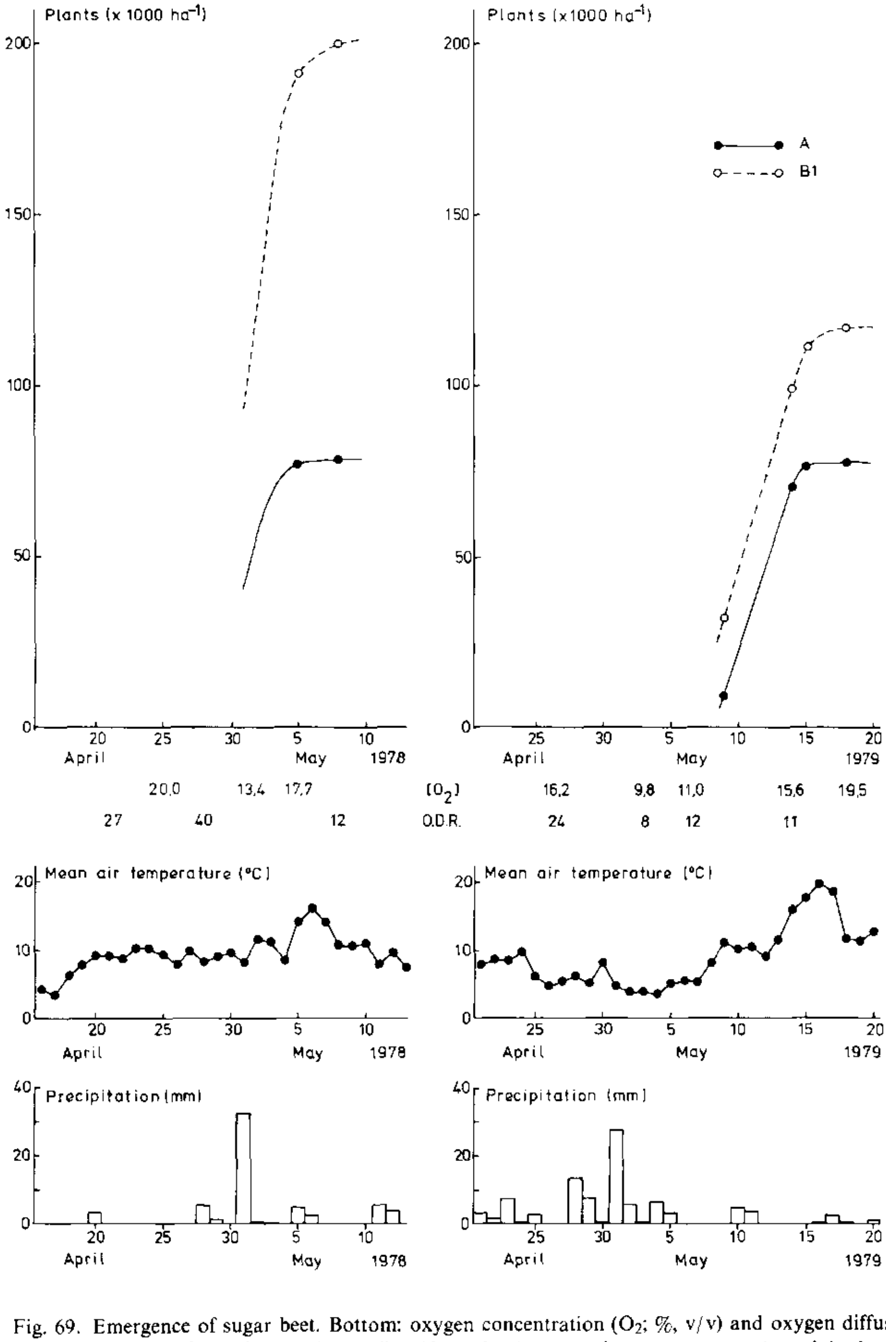

Fig. 69. Emergence of sugar beet. Bottom: oxygen concentration (O_2; %, v/v) and oxygen diffusion rate (O.D.R.: 10^{-8} g cm^{-2} min^{-1}) in untilled soil at 10 cm depth, mean air temperature and precipitation.

Table 83. Plant densities (plants m $^{-2}$) after final emergence of sugar beet in research plots and in the surrounding experimental field.

System	1978				1979			
	field			research plot	field			research plot
A	8.1	8.2	7.8	7.8	7.4	7.7	6.4	7.9
B1	20.5	18.9	20.8	20.0	11.4	12.4	12.8	11.7

B1, respectively. Because sowing distance in the row was 15.5 and 11 cm in Systems A and B1, mean plant density was adequate in System A and beyond optimum in System B1. Plant density in the row was, in general, more uniform in System B1 than in System A. Plant density in System B1 was only irregular in dips with prolonged ponding after the heavy rainfall on 2 May. Plant densities on the research plots were about the same as on other plots of the experimental field.

9.3.3 Soil water

The depth of the groundwater table in the middle between drains, was quite similar for tilled and untilled soil (Figs. 70 and 72). In April and May, when the groundwater table was close to drainage depth (1.1 m) it was in 1978 5 – 10 cm and in 1979 3 cm deeper in the tilled than in the untilled soil. Differences between systems were somewhat larger in early June 1978 (up to 15 cm) and in early July 1979 (up to 7 cm) but later in the season when the water table gradually fell, differences gradually disappeared. Differences of 2.4 and 2.9 cm in 1978 and 1979, respectively, can be explained by differences in pore space of the arable layer. Measurements of surface elevation at the start of the experiment in 1972 showed no difference between the two 1979 research plots. In 1978, the surface elevation of the ploughed plot was somewhat higher (up to 10 cm) than the untilled plot.

Fluctuations of the groundwater table were also very similar for the tilled and untilled plots. For instance, on 2 May 1978, after 32 mm of rain on 1 May, the depth of the water table was 40 cm and 33 cm, and three days later 88 cm and 75 cm in System A and B1, respectively. Comparable figures were obtained for the 1979 growing season. From measurements of soil water potential during the very wet first part of the 1979 growing season, with 235 mm rainfall between 20 April and 20 June, it can be concluded that water movement in during 8 years untilled soil was not seriously hampered (Figs. 70 and 71). In the arable layer soil water potentials were about the same in both systems. Soil water potentials at greater depths were, in accordance with the slightly deeper groundwater table, slightly more negative in System A than in System B1. During rainy periods in spring, soil water potentials of the arable layer were considerably less negative than – 10 kPa. During the first (1 May) and second (end of May) wet period, part of the arable layer was even nearly saturated, especially on the untilled soil. After the third wet period (mid-June), soil water potentials in the arable layer became more negative than – 10 kPa, but never more negative than – 100 kPa. The decrease was somewhat faster in System A than in System B1. During rainy periods later in the season soil water potentials increased considerably and they even temporary became less negative than – 10 kPa. At

In 1979 the soil remained wet until mid-June. On 18 June the arable layer was again close to field capacity. The root system was still restricted to this layer and even at the beginning of July only a few roots had passed the ploughpan (see also Subsection 9.3.6). Between 18 June and 16 July (potential evaporation 98 mm and 20 mm rain) soil water content therefore decreased mainly in the arable layer and clearly more in System A than in System B1. Soil water depletion was similar in the 0 – 10 cm layer of both systems, but decreased more with depth in System B1 than in System A. Between mid-July and mid-August (potential evaporation 82 mm and 62 mm rain) soil water content increased in the 0 – 20 cm layer of System A and only in the 0 – 10 cm layer of System B1. This indicates that in the arable layer the roots of System B1 were more active than of System A. In this period soil water content in and below ploughpan depth decreased considerably on both systems. This is in agreement with the root count data.

9.3.4 Soil aeration

Soil oxygen concentration in the soil profile was always higher in System A than in System B1. The difference was large during wet periods and diminished strongly when soil water contents decreased (Fig. 75).

In 1978, in the arable layer low oxygen concentrations (< 10%, v/v) were never found. Lowest concentrations were obtained during emergence after heavy rainfall when the soil was at field capacity. At that time the oxygen consumption was still low because soil temperature was low and there were only a few sugar beet roots. In the next two months, water contents steadily decreased and, therefore, gas diffusion strongly improved. In spite of higher soil temperatures and an increasing amount of respiring roots, oxygen concentrations steadily increased. In System A, soil oxygen concentration in the C horizon decreased only slightly with depth but in System B1, where soil water content was slightly higher, gas diffusion was more inhibited. At emergence, even at a depth of 40 cm, the oxygen concentration decreased clearly below 10% (v/v). However, also here a small increase in air content improved gas diffusion considerably. In the last week of May, when the first roots had reached the ploughpan, oxygen concentrations were already far above critical levels. In June they were high in both systems at all depths.

In 1979, during the first wet period just before emergence, in the arable layer of System B1, oxygen concentrations decreased to about 10% (v/v). Soil water potentials were very high and therefore some diffusion wells temporarily filled with water on both systems. In the C horizon oxygen concentrations decreased only slightly with depth during the whole growing season and in a comparable way in both systems. This is in accordance with the only small difference in depth of the groundwater table. During the second wet period at the end of May, oxygen concentrations at 10 cm depth in the untilled soil did not decrease much, but at greater depths concentrations were comparable with those of the first wet period. This is understandable because the second wet period occurred 2 weeks after emergence and the root system was still very small. During the third wet period, mid-June, oxygen concentrations were somewhat higher than during the second wet period. This was related to somewhat less rain and increased evapotranspiration and, thus, to lower soil water contents. Roots at the rooting front of System A have always grown at high oxygen concentrations (Fig. 76). In the arable layer of System B1 these concentrations were also high during the first two weeks after emergence, but during the

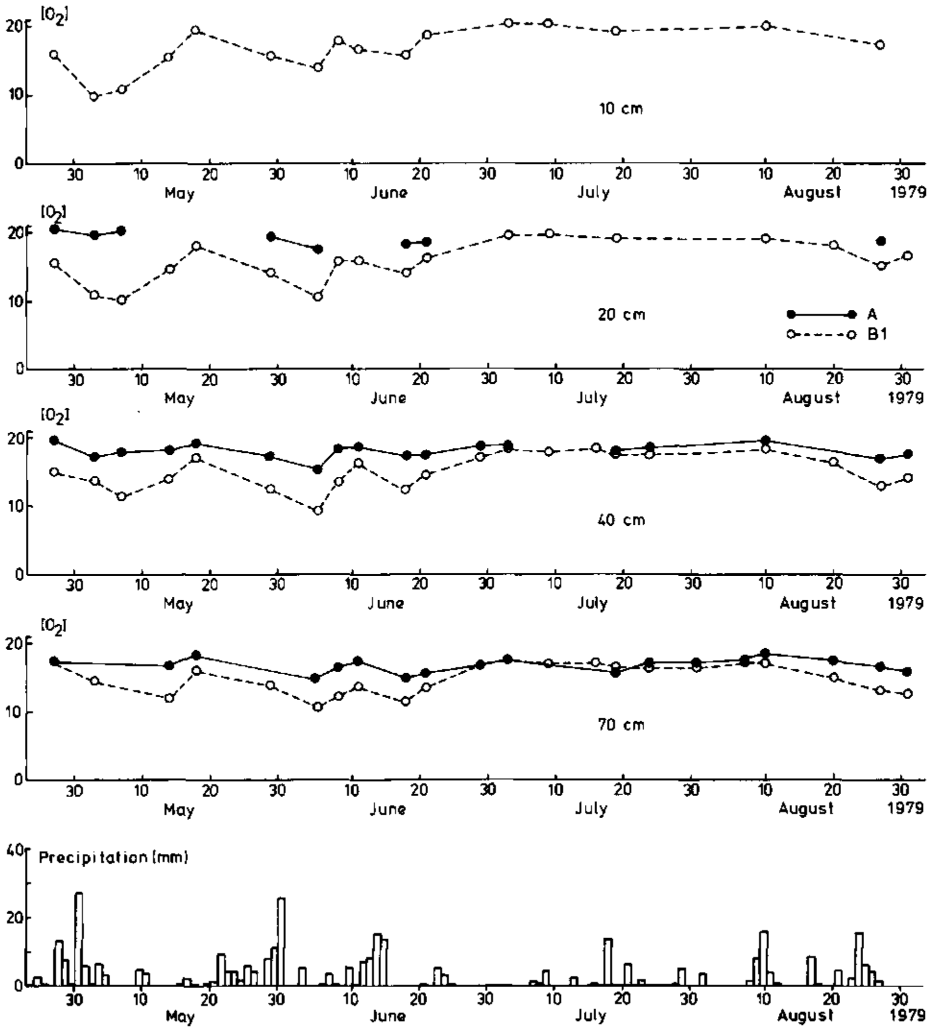

Fig. 75. Precipitation and soil oxygen concentrations at several depths in sugar beet plots in 1979.

wet period at the end of May concentrations decreased to values between 10 and 15% (v/v). Later on, also in System B1, the root system always developed at high oxygen concentrations.

The Oxygen Diffusion Rate (O.D.R.) showed a large variability with time and somewhat more in the arable layer of System B1 than of System A. In the arable layer of the untilled soil during wet periods and high soil water contents, mean O.D.R. was <20 10^{-8} g cm^{-2} min^{-1}, which is to be considered as insufficient (Letey & Stolzy, 1964). In the ploughed layer of System A, critical mean values of O.D.R. were not found. Differences between tilled and untilled soil were greater at a depth of 10 cm than at a depth of 20 cm, probably because in System A straw and stubbles of spring barley and grass green

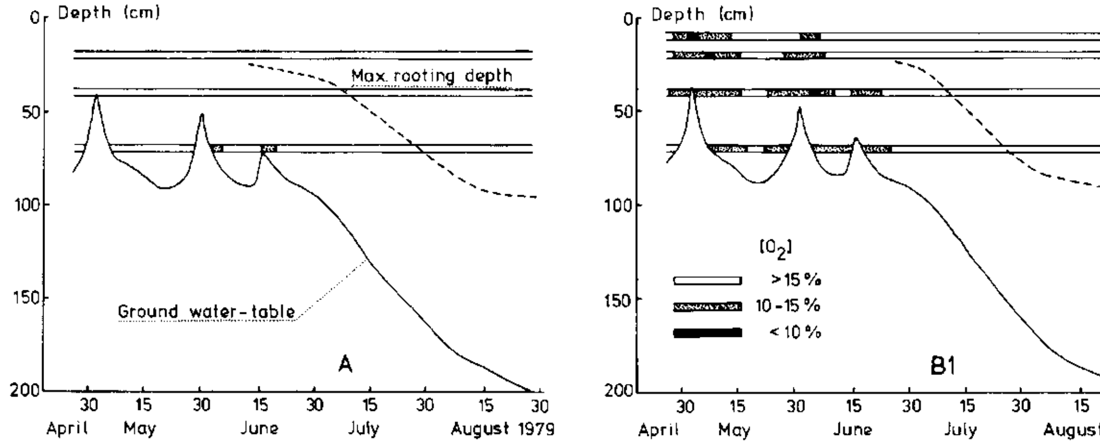

Fig. 76. Groundwater table, maximum rooting depth and soil oxygen concentrations in sugar beet plots in 1979.

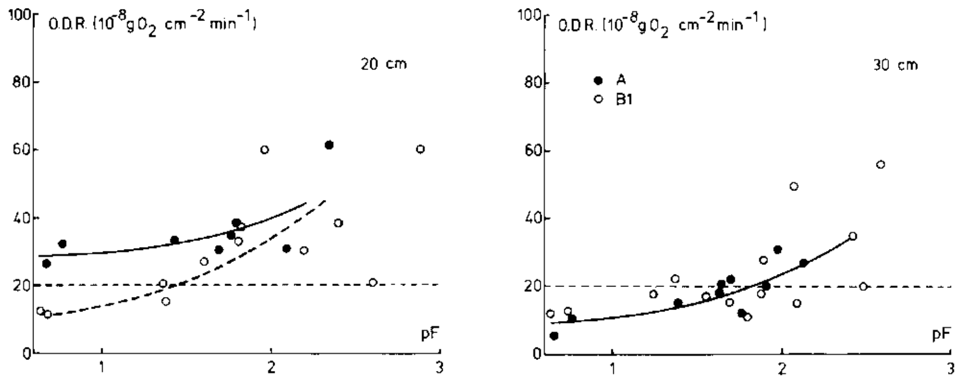

Fig. 77. Relationship between oxygen diffusion rate (O.D.R.) and soil water potential in the arable layer (20 cm depth) and ploughpan (30 cm depth) in sugar beet plots in 1979.

manure were ploughed in. Critical values in the loose arable layer of System A can only be expected near saturation (Fig. 77), a situation which is very rare under the conditions studied. In the dense untilled soil of System B1, however, critical values of O.D.R. were already obtained at soil water potentials less negative than −3 kPa. At ploughpan depth of both systems this happened even at −7 kPa.

Mean O.D.R. values, soil water contents and soil water potentials, rainfall data and relations between relevant parameters for each system and depth, allowed the estimation of the length of the periods with insufficient O.D.R. (Fig. 78). It can be concluded that in the untilled arable layer of System B1, critical situations at 10 cm depth only occurred during rainy periods in spring when evapotranspiration was low and soil water content still high. These periods were substantial in 1979 but not in 1978. At a depth of 20 cm, which is below the most compacted part of the arable layer, critical periods were somewhat shorter than at a depth of 10 cm and they were nearly absent in 1978. In both

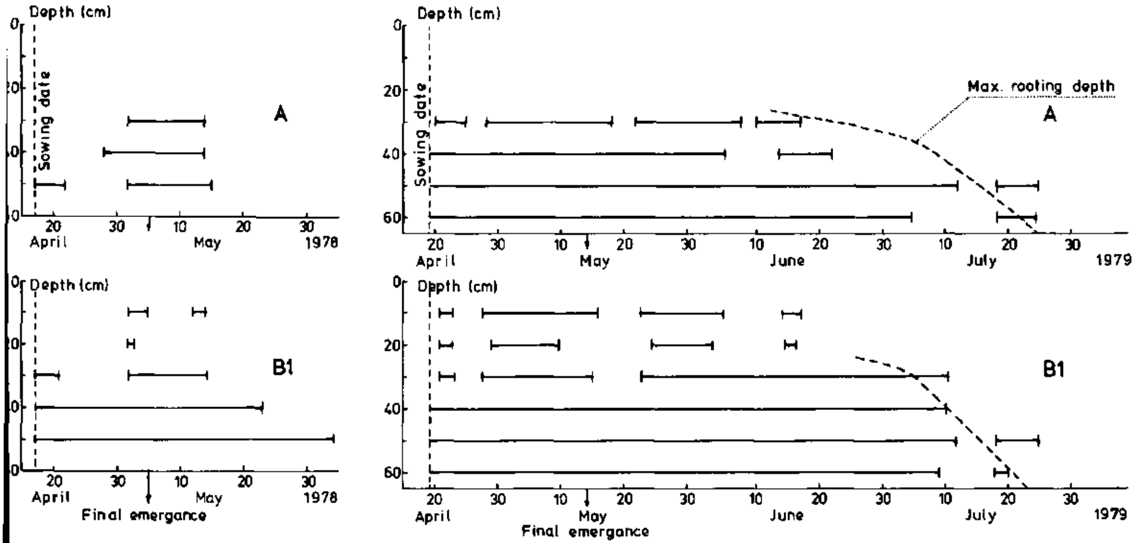

Fig. 78. Periods during which the oxygen diffusion rate (O.D.R.) was $<20 \times 10^{-8}$ g cm^{-2} min^{-1} in sugar beet plots in 1978 and 1979.

systems, the ploughpan and deeper soil layers, in particular, had insufficient O.D.R. values for a much longer time. In 1978 there was no real difference between tillage systems at ploughpan depth but at greater depths, due to higher moisture contents, O.D.R. values were critical for a longer time in System B1 than in System A. At the time the first roots had reached ploughpan depth (the last week of May) the O.D.R. of this layer was already sufficient in both systems. In the C horizon the root system of both systems also developed at a sufficient O.D.R.

In 1979, the soil in or just below the ploughpan of System A had an insufficient or nearly insufficient O.D.R. up till the end of the third wet period. In System B1 this period with inadequate aeration lasted more than two weeks longer. Probably this was caused by an accumulation of roots above the ploughpan in System A and a much smaller root density and subsequent smaller water extraction at this depth in System B1. Deeper in the soil profile there were no systematic differences between tillage systems. In the C horizon, root growth to depth was quite rapid in both systems although the first roots sometimes penetrated soil with an insufficient mean O.D.R. Once the roots had entered, aeration improved rapidly by water extraction and always stayed above the critical level.

9.3.5 Cone resistance

Relations between mean cone resistance and soil water content were obtained for each system and depth. From the more frequently measured water contents and these relationships, it was possible to estimate cone resistance throughout the whole growing season (Fig. 79).

Cone resistance in the ploughed layer in System A was low for a long time. Except during wet periods, when values decreased below 1 MPa, cone resistances usually varied

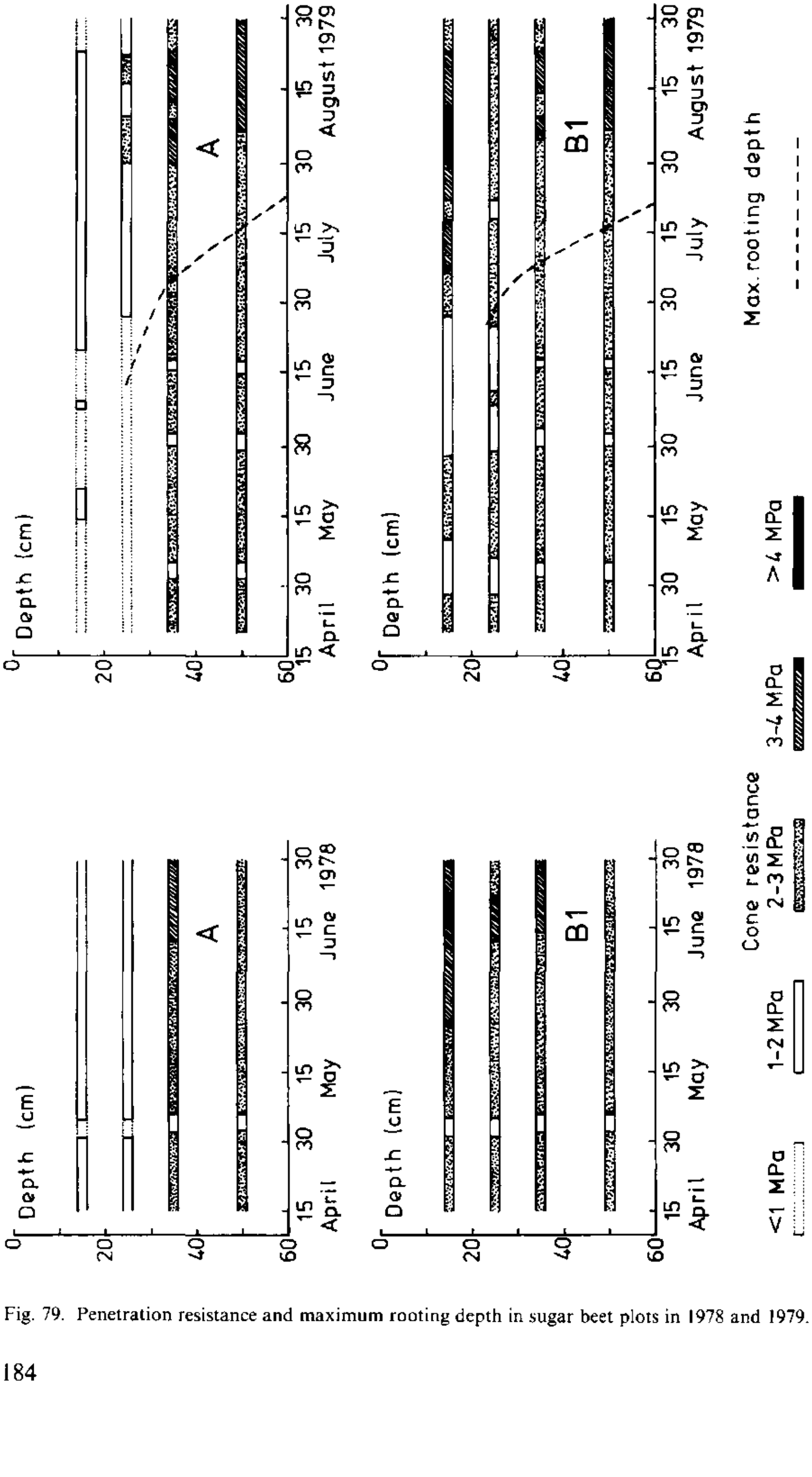

Fig. 79. Penetration resistance and maximum rooting depth in sugar beet plots in 1978 and 1979.

between 1 and 1.5 MPa. Values hardly reached 2 MPa in the driest part of June 1978. Because in 1979 pore space was somewhat higher and rainfall more abundant, cone resistances were quite often below 1 MPa up till mid-June. In this year, values did not increase above 2 MPa in the upper part and not until August in the lower part of the arable layer.

At the beginning of the growing season, cone resistance in the untilled arable layer of System B1 varied between 2.5 and 3 MPa in 1978 and between 2 and 2.5 MPa in 1979. Because the inverse dependence of cone resistance on soil water content is much greater in a dense than in a loose soil (Boone et al., 1978), cone resistance fluctuated much more in System B1 than in System A. Cone resistances in System B1 decreased just below 2 MPa during wet periods and therefore more often in 1979 than in 1978. However as the soil water content decreased a little, values increased sharply. In 1978 values at a depth of 15 cm increased above 3 MPa in the last week of May. Two weeks later this occurred at a depth of 25 cm. Mid-June the soil at a depth of 15 cm had temporary cone resistances above 4 MPa. In 1979 values at this depth did not increase above 3 MPa until the first week of July and only temporarily increased above 4 MPa in August. Cone resistances at a depth of 25 cm always stayed below 3 MPa.

At the beginning of the growing season the untilled arable layer and the soil at ploughpan depth in System B1 had similar cone resistances. However, cone resistance in the ploughpan of System A was slightly higher (Fig. 80: left). Because soil water depletion was less, cone resistance at ploughpan depth increased more slowly and to a lower level than in the most dense part of the untilled arable layer in System B1. When soil water content decreased, values at ploughpan depth exceeded 3 MPa a few days earlier in System A than in System B1. Cone resistances at ploughpan depth were always somewhat higher in System A than in System B1.

Cone resistances of the soil below the ploughpan sometimes exhibited considerable

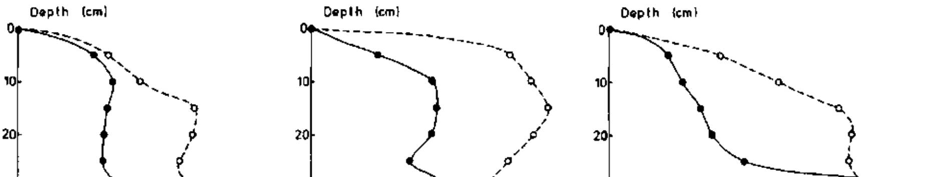

Fig. 80. Penetration resistance in spring (18/4/1978: soil moisture in equilibrium with a groundwater table of 1 m), in early summer (12/7/1979: relatively dry soil conditions in arable layer) and in late summer (14/8/1979: relatively dry soil conditions, especially in subsoil).

spatial variability and variability between depths. At the start of the growing season values were similar with those of the untilled topsoil in System B1. In first instance soil water content decreased more in the topsoil than in the subsoil and therefore cone resistances increased more in the untilled topsoil than in the subsoil (Fig. 80: middle). Later on differences reversed and consequently cone resistances exceeding 3 MPa were found in the whole soil profile of System B1 (Fig. 80: right).

In 1978, the first roots reached the ploughpan before the last week of May. In 1979 this occurred about one month later. In both years extension of the rooting front proceeded at cone resistances close to values measured at sowing when soil water was in equilibrium with a groundwater table of 1 m (Fig. 79). However, in 1978 most root branching occurred at lower soil water contents, which means high cone resistances in the untilled topsoil. In 1979, in contrast, root branching in the untilled topsoil occurred for more than one month at relatively high soil water contents and intermediate cone resistances.

9.3.6 Root growth

In 1978, maximum rooting depth one month after emergence was about 40 cm in both Systems A and B1 (Fig. 81). Root density in the ploughpan was also similar at that moment but later it increased somewhat faster in System B1 than in System A (Table 84).

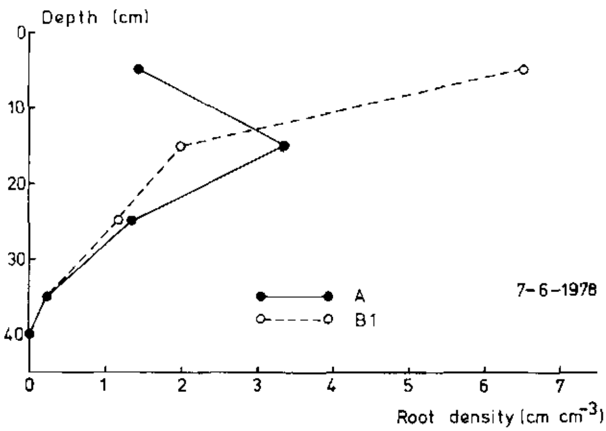

Fig. 81. Distribution of the root density determined from soil cores with depth in sugar beet plots on 7/6/1978.

Table 84. Sugar beet root density (cm cm^{-3}) in and just below the ploughpan 4 and 6 weeks after emergence in 1978.

Depth (cm)	System A		System B1	
	7/6	20/6	7/6	20/6
32 - 37	0.23	0.37	0.22	0.45
42 - 47	0.00	0.28	0.00	0.37

When a linear increase in root density is assumed, the ploughpan of Systems A and B1 should have been reached 2 weeks and within 3 weeks after emergence, respectively. Taproot elongation in the arable layer, therefore, may have been slightly faster in the ploughed than in the untilled soil. The transition of the loose ploughed soil to the very dense ploughpan was a temporary barrier for the roots of spring barley (Chapter 8). The limited observations of the root system (see also Subsection 9.2.3), however, dit not allow to draw such a conclusion for sugar beet.

In the beginning of the very wet growing season of 1979, root growth to depth was much slower. More than 7 weeks after emergence maximum rooting depth was only 35 cm in System A and 30 cm in System B1 (Fig. 82). Taproot elongation in the arable layer, therefore, was slightly more hampered in System B1 than in System A. In System A there was a pronounced accumulation of roots just above the ploughpan (Fig. 83).

Comparison of the 1978 and 1979 observations indicates that the dense ploughpan was impeding sugar beet root extension more under wet than under drier soil conditions. Nevertheless, because the ploughpan was reached a little earlier, the number of roots that were present in the ploughpan in the beginning of the growing season was still somewhat higher in System A than in System B1. Later on, in both years the reverse was found. Between 7 and 20 June 1978 root densities increased with 0.14 and 0.23 cm cm^{-3}, whereas cone resistances measured on 14 June were 3.7 and 3.0 MPa in Systems A and B1,

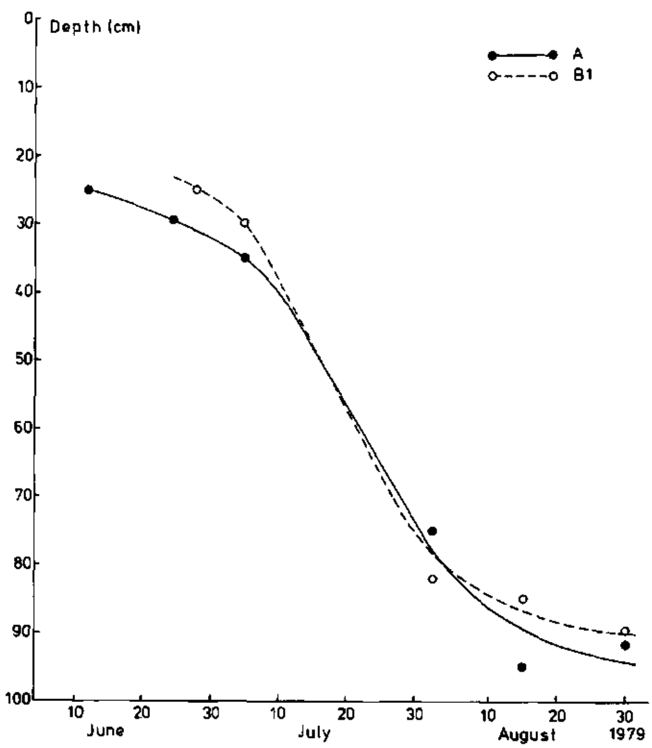

Fig. 82. Depth of the rooting front in sugar beet plots in 1979.

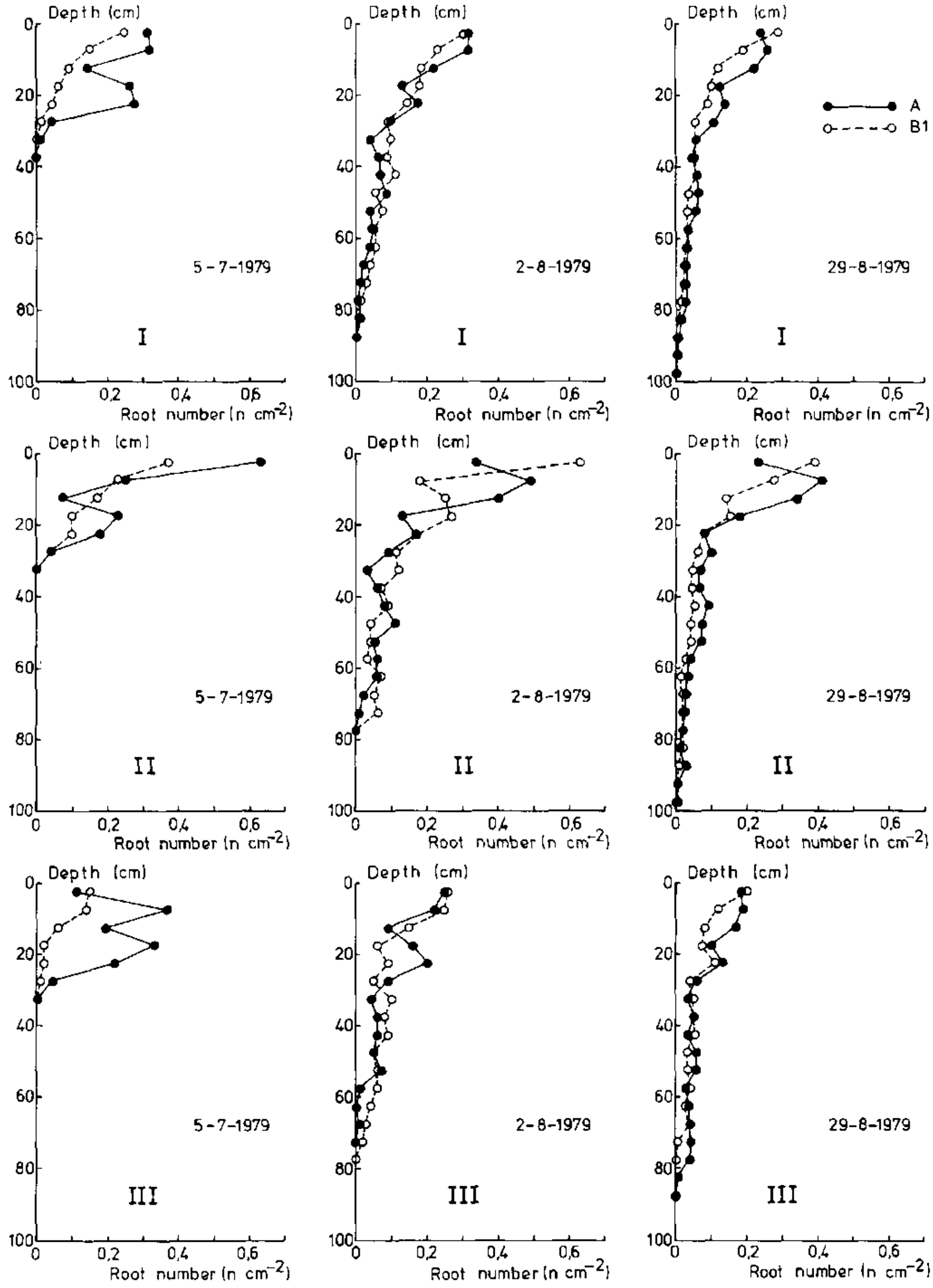

Fig. 83. Distribution of the number of roots counted on vertical profile walls with depth in sugar beet plots on three dates in 1979. I = mean, II = in crop rows, III = in the middle between crop rows.

respectively. Root growth in the ploughpan was, therefore, slow at both cone resistances but did not decrease very much at values >3 MPa. Even a cone resistance of 4 MPa probably would not have fully prevented root growth.

In 1978, one month after emergence, root density in the top layer of the crop row was much higher in System B1 than in System A. In 1979 this was observed only later in the growing season (Fig. 84II). In 1978, early shoot growth was also better in System B1 than in System A, but in 1979 the reverse was found (see also Subsection 9.3.7). In 1978, root density in the crop row of the arable layer decreased very sharply with depth in System B1. In System A more roots were counted in the middle of the ploughed layer than in the top layer. In the beginning of the wet 1979 growing season, the number of roots in the crop row decreased very sharply with depth in both systems. In the middle, between crop rows, clearly more roots were counted in ploughed than in untilled soil. Only in System A did roots accumulate just above the ploughpan. The total number of roots in the arable layer was larger in System A than in System B1, especially in the middle between crop rows (Figs. 84 and 85). Differences decreased in July and were relatively small in August. In August, root numbers decreased somewhat in both systems.

In 1979, below the ploughpan root growth to depth was faster than in the ploughpan (Fig. 83), perhaps even faster in System B1 than in System A. Ultimate maximum rooting depth, however, was slightly greater in System A. Maximum depths in the crop row were about 10 cm greater than in the middle between rows. At the beginning of

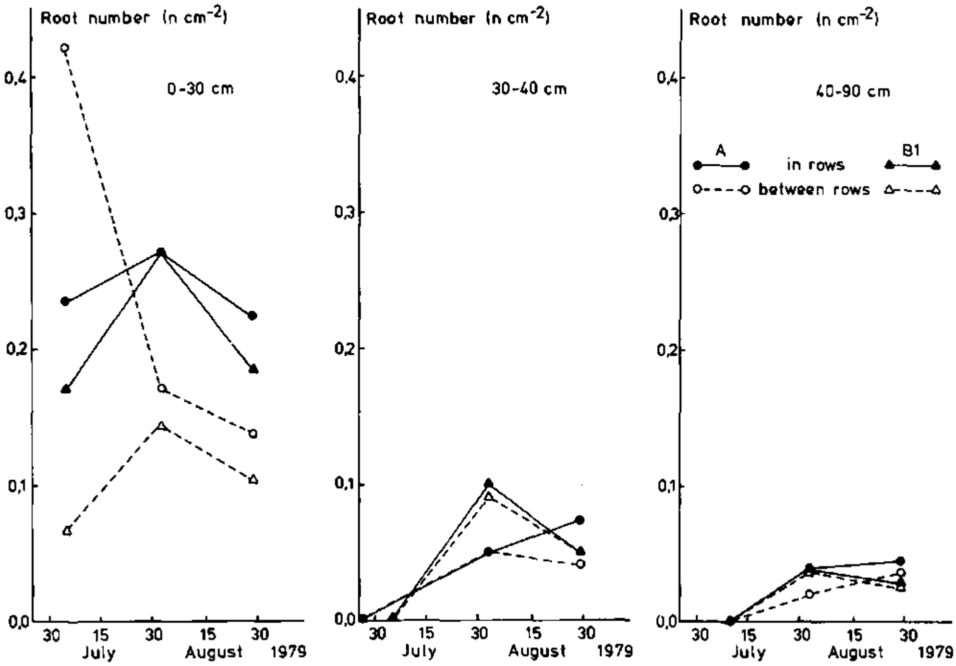

Fig. 84. Development of the number of sugar beet roots counted on vertical profile walls with time in several characteristic soil layers in 1979.

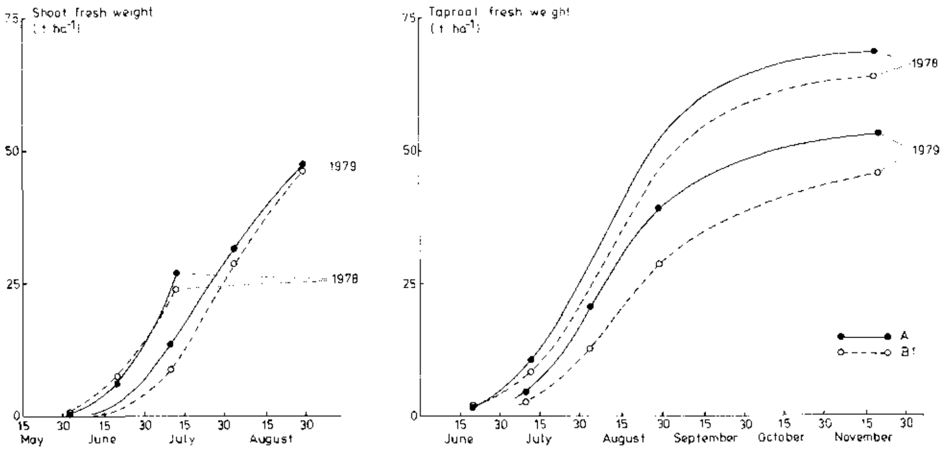

Fig. 85. Shoot and taproot growth of sugar beet in 1978 and 1979.

August the number of roots below the ploughpan was higher in System B1 than in System A. Accumulation of roots above the ploughpan of System A was more pronounced in the middle between crop rows than in the rows. Apparently many roots failed to penetrate the ploughpan in the middle between rows and, therefore, fewer roots were found below the ploughpan. In the beginning of August the number of roots below the ploughpan in the middle between crop rows relative to the number of roots in the rows was 50 and 90% for Systems A and B1, respectively. Root numbers at both positions decreased during August in System B1 but still increased, especially in the middle between rows, in System A; and the relative root numbers changed to 82 and 86% for Systems A and B1, respectively.

9.3.7 Shoot and taproot growth

In 1978 the sugar beets were sown on 17 April, and in 1979 on 19 April. In 1978, emergence was completed on 5 May, but in 1979 on 14 May. In 1979 also shoot and taproot growth started at a lower rate than in 1978 (Fig. 85). This was related to a higher rainfall and a lower evapotranspiration. Heavy rainfall at the end of May and mid-June 1979 obviously delayed crop growth in both systems, but especially in System B1 it showed temporarily a lighter green colour than usual. After this wet period, crop growth accelerated considerably, but never compensated for this early delay. Therefore, final yields were significantly lower in 1979 than in 1978.

In 1978 mean plant density after emergence was adequate in System A (78 000 plants per ha) and far too high in System B1 (200 000 plants per ha). Singling by hand at the end of May reduced this density to 100 000 plants per ha. Final plant distribution was good on the untilled but less uniform on the ploughed soil.

Early shoot growth was better in System B1 than in System A. Shoot fresh and dry weight per plant one month after emergence were 12 and 21% higher, respectively, on the untilled than on the ploughed soil (Table 85). In June, with a high evapotranspiration and a low amount of rainfall, the top layer dried out and shoot growth of System B1

Table 85. Plant number, shoot fresh weight on plant and area basis and dry matter content of sugar beet at several dates in 1978 and 1979.

Year	Date	Plant number × 1000 ha⁻¹		Shoot fresh weight				Dry matter content (%)	
				g plant⁻¹		t ha⁻¹			
		A	B1	A	B1	A	B1	A	B1
1978	2/6	71.0	103.0	5.2	5.8	0.37	0.60	8.8	9.7
	20/6	69.0	107.0	90.6	70.5	6.2	7.5	11.3	13.4
	12/7	90.0	92.0	299.2	259.8	26.8	23.8	10.1	9.3
1979	8/6	.	.	4.3	2.4	.	.	8.7	8.8
	10/7	70.5	87.9	187.0	99.0	13.2	8.7	9.8	10.0
	3/8	63.5	90.8	501.0	316.0	31.8	28.7	9.2	8.9
	29/8	85.0	95.0	558.0	487.0	47.4	46.3	11.7	11.2

lagged, therefore, clearly behind. In System B1, shoot fresh weight per plant was 22% less than in System A, but because dry matter percentage was clearly higher, dry matter weight per plant was only 7% lower. Nevertheless, System B1 had a 21% higher shoot fresh weight per ha because plant density on the sub-plots was much higher than in System A (Figs. 86 and 87). Although plants were still rather small, competition between plants probably contributed to the smaller weight per plant in System B1. Taproot fresh and dry weight per plant showed the same tendencies as shoot weight and were 23 and 12% lower, respectively, in System B1 (Table 86; Figs. 86 and 87). Taproot fresh weight per ha was still 21% higher in System B1. Taproots of System B1 had an only 9% smaller maximum diameter but they were 21% shorter than in System A (Table 87). The number of fanged roots was small on the ploughed soil, but about twice as high on the untilled soil.

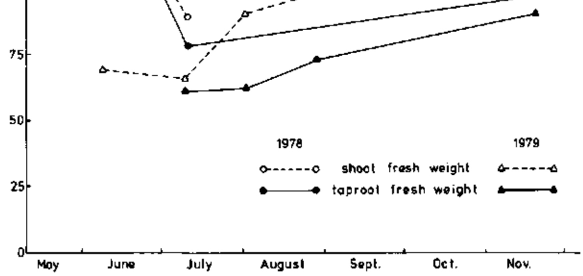

Fig. 86. Shoot and taproot fresh weight of sugar beet in System B1 relative to System A.

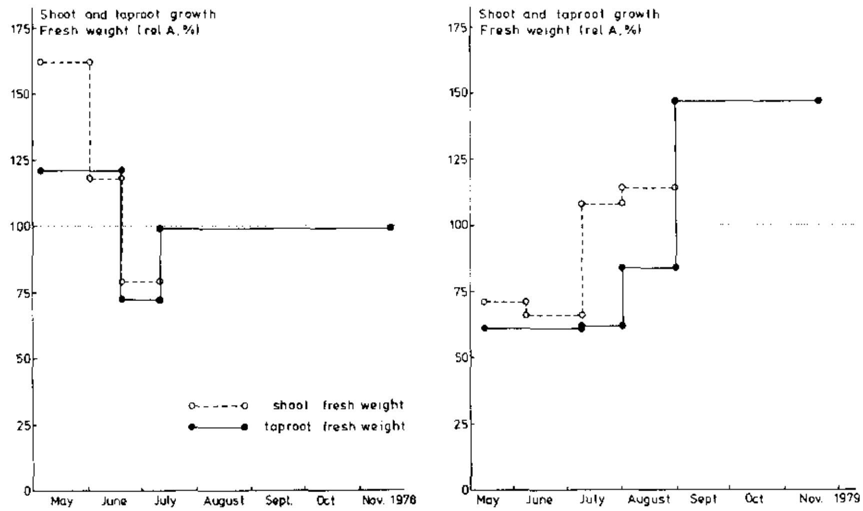

Fig. 87. Increase in shoot and taproot fresh weight of sugar beet in System B1 relative to System A in several periods of 1978 and 1979.

Table 86. Taproot weight on plant and area basis at several dates in 1978 and 1979.

Year	Date	Plant number × 1000 ha⁻¹		Root fresh weight				Dry matter content (%)	
				g plant⁻¹		t ha⁻¹			
		A	B1	A	B1	A	B1	A	B1
1978	20/6	69.0	107.0	20.3	15.7	1.4	1.7	12.9	14.8
	12/7	90.0	92.0	117.2	89.0	10.5	8.2	17.1	17.0
1979	10/7	70.5	87.9	58.0	28.0	4.1	2.5	15.1	15.9
	3/8	63.5	90.8	323.0	140.0	20.5	12.7	17.9	18.6
	29/8	85.0	95.0	461.0	297.0	39.2	28.2	21.6	20.2

Table 87. Shoot: taproot ratio (DM) and taproot characteristics of sugar beet at several dates in 1978 and 1979.

Year	Date	S/R		Taproot length[a] (cm)		Max. taproot diameter (mm)		Fanged roots (%)	
		A	B1	A	B1	A	B1	A	B1
1978	20/6	3.9	4.0	9.9	7.8	25.9	23.5	8	18
	12/7	1.5	1.6	17.8	13.4	.	.	4	10
1979	10/7	2.1	2.2	12.6	6.9	.	.	.	.
	3/8	0.8	1.1	22.0	13.0	.	.	32	75
	29/8	0.7	0.9	24.0	18.0	.	.	34	67

a. From top to a diameter of 0.5 cm.

Rainfall between 20 June and 12 July decreased dry matter content but more in System B1 than in System A. On 12 July the sub-plots for yield determinations had similar high plant densities and, therefore, values on plant or area base were similar. Fresh and dry shoot weight were 13 and 20% lower, respectively, in System B1 than in System A. For the taproot these percentages were 24 and 25, respectively. Shoot growth, therefore, was less depressed than taproot growth, which was also expressed by a slightly higher shoot: root ratio.

At the perennial nitrogen levels P⁻, P and P⁺, final root yields in System B1 were 17, 4 and < 1% lower than in System A (Table 88). At P⁻ sugar content in System A was only slightly higher than in System B1, but at higher nitrogen levels it decreased more in System A than in System B1. Similar maximum sugar yields were obtained at P⁻ in System A and at P⁺ in System B1.

In 1979 mean plant density after emergence was adequate in System A (79 000 plants per ha) but beyond optimum in System B1 (117 000 plants per ha). Singling by hand at the end of May reduced this density to 98 000 plants per ha. In general, final plant distribution was good on the untilled but less uniform on the ploughed soil.

Three-and-a-half weeks after emergence, about one week after the second wet period, shoot fresh and dry weight per plant was nearly 44% lower on the untilled than on the ploughed soil (Table 85). This might be explained by a temporarily insufficient aeration in the untilled soil. Aeration in the untilled arable layer was also insufficient for some time in the third wet period. Nearly two months after emergence, shoot fresh and dry weight per plant were 47 and 46% lower in System B1 than in System A. Because in System B1 plant density on the sub-plots was clearly higher, shoot fresh and dry weight per ha were 34 and 33% lower, respectively, than in System A. In System B1, taproots were 45% shorter (Table 87) and taproot fresh and dry weight per plant were 52 and 49% lower, respectively, than in System A (Table 86).

Differences in shoot fresh and dry weight between both systems gradually decreased later in the growing season. On a plant basis, differences in the beginning of August were still 37 and 39%, respectively. Competition between plants probably contributed to the smaller plant weights in System B1 because plant density on the sub-plots was 43% higher in System B1 than in System A. Differences between systems in shoot weight per hectare were, therefore, only 10 and 13%, respectively. For the taproot these percentages were still 38 and 36%, respectively. Shoot growth therefore was clearly less depressed than taproot growth. This was also expressed in a clearly higher shoot: root ratio. In this wet growing season, about one-third of all taproots were fanged in System A, but in System B1 this was even two-thirds. The degree of fanging was also more severe on the

Table 88. Root yield, sugar content and sugar yield of sugar beet at final harvest.

Year	System	Root yield (t ha^{-1})			Sugar content (%)			Sugar yield (t ha^{-1})		
		P⁻	P	P⁺	P⁻	P	P⁺	P⁻	P	P⁺
1978	A	68.7	66.7	70.1	17.5	17.6	16.8	12.0	11.7	11.8
	B1	57.3	64.1	69.6	17.4	17.2	17.1	10.0	11.0	11.9
1979	A	53.0	51.5	55.2	17.8	17.8	17.6	9.5	9.1	9.7
	B1	41.6	46.3	48.5	17.6	17.3	17.2	7.3	8.1	8.4

Table 89. Degree of fanging and length of taproot at two dates in 1979.

Date	System	Not fanged		Moderately fanged		Strongly fanged	
		(%)	length (cm)	%	length (cm)	%	length (cm)
3/8	A	68	23	20	23	12	17
	B1	25	15	25	13	50	13
29/8	A	66	24	19	23	15	22
	B1	33	19	37	20	30	15

untilled soil (Table 89).

Differences between systems in shoot weight per hectare had nearly disappeared by the end of August, but differences in taproot fresh and dry weight were still 28 and 33%, respectively. On the untilled soil dry matter content of shoot and taproot were lower than on tilled soil, which indicates that the sugar beet crop was in a younger physiological stage.

In 1979, plant weights at different annual nitrogen applications were measured at two dates. In both systems nitrogen increased taproot and especially shoot weight considerably (Fig. 88). About 7 weeks after emergence both plant parameters increased nearly linearly with nitrogen. Relative increases in shoot and taproot weight at nitrogen application rates of 0 – 300 kg ha^{-1} were somewhat greater in System B1 than in System

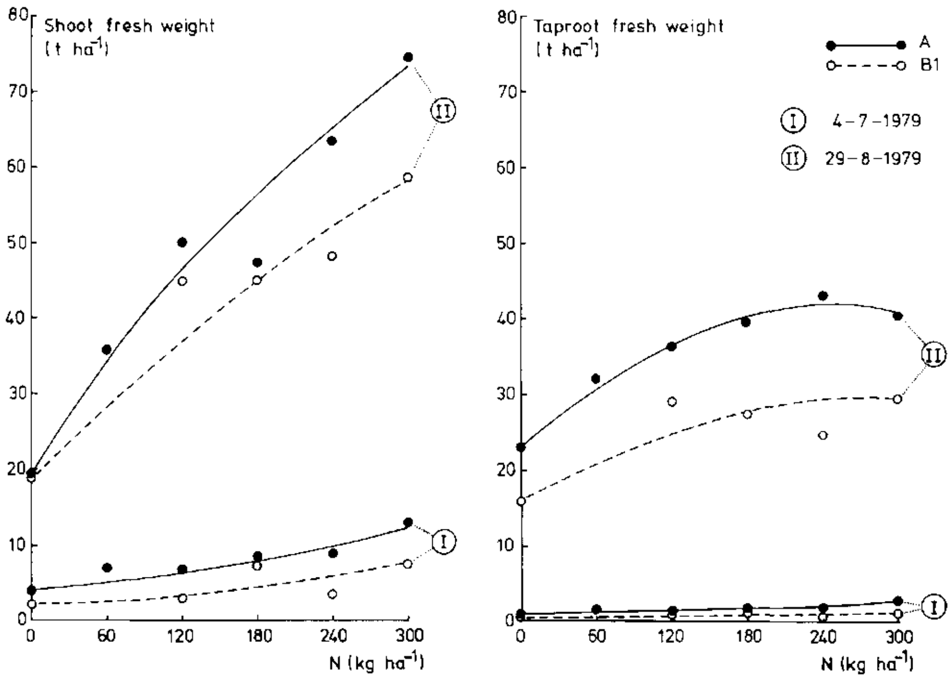

Fig. 88. Effect of nitrogen application on shoot and taproot fresh weight of sugar beet at two dates in 1979.

A. However, because shoot and taproot weights were larger, absolute increases were larger in System A.

At the end of August, shoot weight strongly increased with increasing nitrogen dressings. Nitrogen response, both relative and absolute, was larger in System A. Shoot and taproot dry matter content, in general, were somewhat smaller in System B1 (Fig. 89) but in both systems values decreased slightly at higher nitrogen applications.

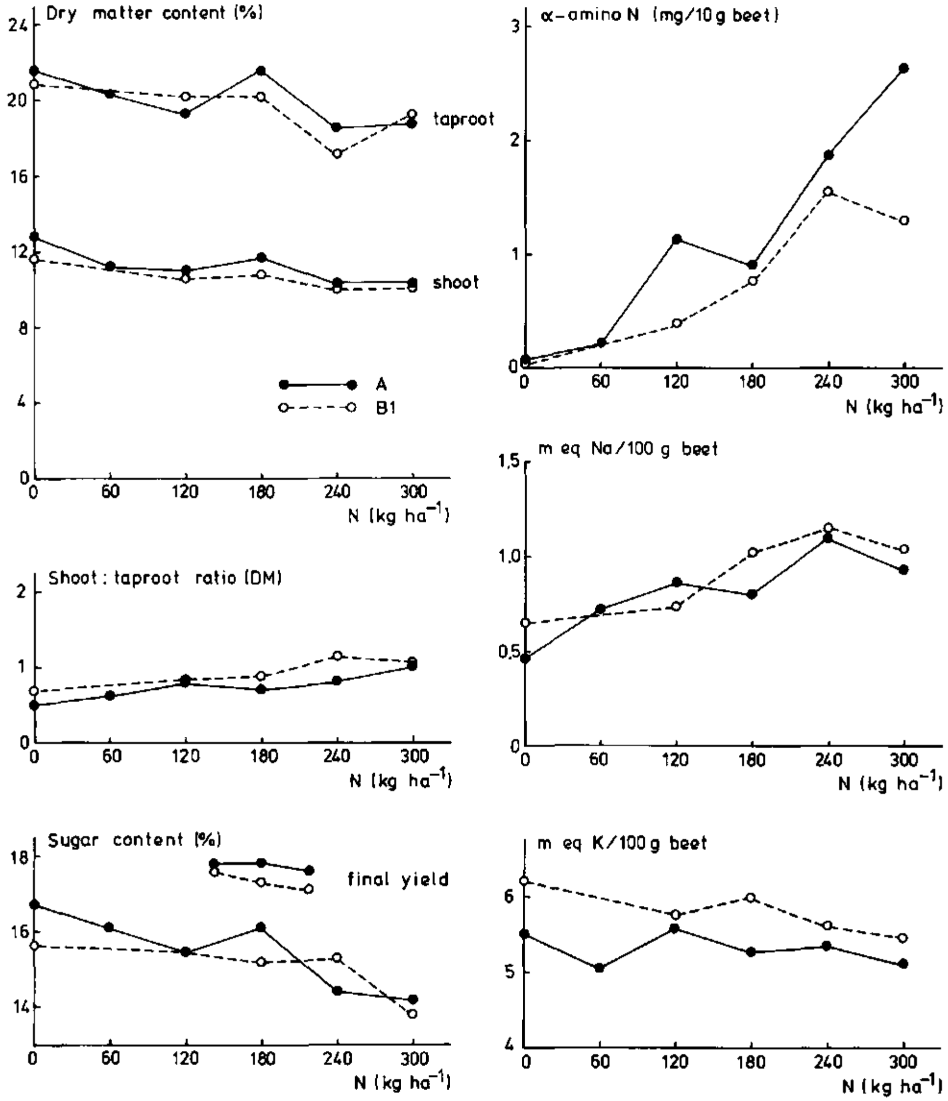

Fig. 89. Effect of nitrogen application on dry matter content of shoot and taproot of sugar beet, shoot : taproot ratio (DM), sugar, α-amino-N, Na and K contents of taproots on 29/8/1979 and on sugar content at final harvest.

Taproot weight in both systems increased clearly only for applications of 0 – 180 kg ha^{-1}. In absolute sense, nitrogen response was again larger in System A. Shoot: root ratio (DM) was higher in System B1. Nitrogen increased this ratio in a similar way in both systems. Sugar content of the taproot was somewhat higher in System A. The amounts of K and Na were somewhat higher but the amount of α-amino-N was somewhat smaller in System B1 than in System A.

At the perennial nitrogen levels P^-, P and P^+ final root yields in System B1 were 22, 10 and 12% lower than in System A (Table 88). At nitrogen level P^-, sugar content in System A was slightly higher and, at higher nitrogen levels, it decreased somewhat less than in System B1. In both systems, maximum sugar yields were obtained at nitrogen level P^+. Maximum sugar yield was 13% lower in System B1 than in System A.

9.4 Discussion

In 1978 and 1979, to improve superficial soil drying and workability, the untilled soil of System B1 was harrowed some time before seedbed preparation for sugar beet. Although soil water content of the top 3 cm was still higher than in the ploughed soil of System A, by a very intensive seedbed preparation, a seedbed of a sufficient quality could be prepared. In both years in System B1, emergence was even slightly better and stand was more regular than in System A.

In System A, because seedbed preparation and sowing were combined, the soil was not allowed to dry superficially for a few hours and, therefore, adhered to the seed coulters. This sometimes gave rise to clogging and, therefore, irregular sowing. Moreover, because the small sugar beet seed requires a rather fine and shallow seedbed, in places with a rough soil surface, seeds were sometimes dropped between furrows in already dry soil. In System B1, as a consequence of dips and ruts present at seedbed preparation and the shallow working depth of the full-width rotary cultivator, seedbed depth was quite variable. Careful sowing with a precision drill compensated for this potential drawback, as was shown by the favourable 1978 results when seeds germinated without rain of any importance. Obviously, seeds were placed properly at the transition between the seedbed and the dense untilled soil underneath with a high capillary water transport.

However, differences between systems became obvious during heavy rainfall. In System A, although the fine seedbed partially slaked, water infiltrated easily. In System B1, however, the rolled and therefore flat soil surface slaked completely, because, due to a temporarily higher water content, vulnerability to rain drop impact was higher than in the seedbed of ploughed soil. Infiltration of water into such a slaked surface is very slow (Bouma, 1977). Therefore, water ponded at some places and runoff to small dips took place. In the wet spring of 1979, water ponded in some dips during a prolonged period of time. In these spots, aeration was poor and, therefore, emergence was slow and insufficient. However, the total ponded area was only small.

From the observation that in many places epicotyls buckled, it may be concluded that upon drying severe crust formation was a more serious potential hazard than insufficient aeration. However, during the experiment this risk was masked because at the critical moment enough rain fell to soften the hard crust.

From the similar soil water potentials measured during the wet early 1979 growing season, it may be concluded that in the untilled soil movement of water was no more hampered than in tilled soil. Neither the ploughpan formed a clear barrier for transport of water. Although there may have been differences in soil water potential between systems in shorter intervals than measured, they apparently had no large impact on root and shoot development. In 1979, during the first wet period (beginning of May), soil water potentials in sugar beet and spring barley plots were similar. During the second wet period (end May), values were less negative in sugar beet than in spring barley plots because at that time leaf area, and therefore evapotranspiration, was much larger in spring barley than in sugar beet.

In early spring, when the soil was at field capacity, differences in water content between tilled and untilled soil could be explained by differences in water retention curves. These curves were different according to differences in pore space, organic matter content and aggregate size (see also Chapters 3 and 8). In tilled and untilled soil, however, the volume of readily and total available water was similar.

The amount of oxygen available to the root system at a certain depth depends on both macro- and micro-transport of oxygen. Macro-transport occurs by diffusion through the air-filled pore system and is characterized by the gas diffusion coefficient. The soil oxygen concentration depends on the supply of oxygen and the demand of oxygen by the root system and the soil microbes. Micro-transport of oxygen occurs over small distances from the nearest air-filled pores through the soil-water complex to the root surface. This process is simulated by a thin, negatively charged platinum electrode, which reduces oxygen at its surface at a rate (Oxygen Diffusion Rate, O.D.R.) determined by both the soil-water complex and the oxygen concentration at the interface between air and soil-water.

Aeration levels were significantly different in the tilled and untilled soil. At the same soil water potential, air contents were considerably smaller in the untilled soil. This was also found for the gas diffusion coefficients, although, at high soil water potentials, gas diffusion coefficients in untilled soil were somewhat higher than might be expected from the small air contents (Chapter 3). When air contents increased, gas diffusion coefficients increased considerably and, therefore, differences in oxygen concentration with tilled soil diminished rapidly. At intermediate soil water potentials, oxygen concentrations in untilled soil were even high. However, when at the start of prolonged or heavy rainfall, the arable layer was at about field capacity, soil aeration remained sufficient in ploughed but became temporarily insufficient in untilled soil. In both years, such wet conditions occurred around 1 May. At that time, in untilled soil the gas diffusion coefficient was small, but so was the oxygen consumption because soil temperature was low and in the seedbed only a few roots of sugar beet seedlings were present. In untilled soil, the mean oxygen concentration, therefore, did not decrease so sharply. However, the mean O.D.R. decreased to values which are assumed to be insufficient for root growth (Letey & Stolzy, 1964). Because evapotranspiration was still low, mean O.D.R. remained low for some time, especially in the most dense part of the arable layer.

After shoot emergence, soil conditions with respect to aeration in the 1978 and 1979 growing season were different. During May and June 1978 there was clearly less rain than in 1979. In 1978, the differences between systems in root growth in the arable layer cannot be ascribed to insufficient aeration. In untilled soil, mechanical resistance was the major physical factor reducing root growth. In 1979, however, both mechanical resistance and temporarily insufficient aeration were involved. These conclusions are in agreement with the conclusions obtained for spring barley (Chapter 8). During the second wet period, at the end of May 1979, when soil water content was higher and evapotranspiration lower, oxygen concentrations and O.D.R. were low for a longer time than during the third wet period in mid-June. However, in plots with sugar beet, the decrease in oxygen concentration was smaller than in plots with spring barley. This can be explained by a smaller oxygen consumption in the plots with sugar beet because plant density was about one tenth of that of spring barley, and emergence about 2 weeks later than for spring barley. In plots with sugar beet, evapotranspiration was somewhat smaller and, as a consequence, periods with an insufficient O.D.R. slightly longer than in plots with spring barley.

In the ploughed arable layer, the O.D.R. will be insufficient only at very high soil water potentials, close to saturation. In untilled soil insufficient O.D.R. already occurred at soil water potentials less negative than -3 kPa, as occur during prolonged or heavy rainfall in spring. In the ploughpan of both systems this even happened at -7 kPa. In spring, during and after wet periods, the ploughpan and especially deeper soil layers had an insufficient O.D.R. for a long time. Under these conditions there was a sharp contrast in aeration between the ploughed soil and soil layers deeper in the soil profile. In 1978, at the time the first roots had reached ploughpan depth, the O.D.R. of this layer was already sufficient in both systems. Also in the C horizon, the root system of both systems developed at sufficient O.D.R.. In 1979, the soil in or just below the ploughpan of System A had an insufficient or nearly insufficient O.D.R. up to the end of the third wet period. In System B1, this period lasted more than two weeks longer, probably because in the soil above the ploughpan root density and water extraction were smaller. In the C horizon root growth to depth was quite rapid in both systems although the first roots sometimes penetrated soil with an insufficient mean O.D.R.. Once the roots had entered, aeration improved rapidly by water extraction and always stayed above the critical level.

In untilled soil cone resistances were much higher and more variable with water content than in ploughed soil. Typical values at soil water contents close to field capacity were 2 – 3 MPa for untilled and 1 – 1.5 MPa for ploughed soil. At similar water contents, values at ploughpan depth were comparable with those in the untilled arable layer, but they were always slightly higher in System A than in System B1. On average, cone resistances were maximum at a depth of 38 cm in System A and at a depth of 32 cm in System B1. This was a result of a smaller height of the compacted arable layer in System B1 and the presence of a sharp transition from a loose arable layer to a very dense ploughpan in System A. Significant cone resistances at sharp transitions are only obtained at depths several times the diameter of the cone base (about 1 cm). However, soil water content at a depth of 38 cm was slightly higher than at a depth of 32 cm. It therefore can be concluded that higher cone resistances at ploughpan depth in System A may be partly explained by a somewhat stronger developed ploughpan. However, differences in root development may have also contributed in this respect (see also Subsections 9.3.3 and 9.3.6).

During both years, root growth to depth occurred at soil water potentials close to field capacity. In 1978, however, most root branching occurred at lower water contents, which means that in the untilled topsoil cone resistances were high. In 1979, soil water contents remained high for a longer period and, for more than one month, root development proceeded at intermediate cone resistances.

In the arable layer, root growth to depth was only slightly faster in ploughed than in untilled soil. This occurred in spite of more adverse soil conditions and especially a larger cone resistance in the untilled soil. The limited number of observations made support the assumption that in untilled soil the taproot followed the paths of least resistance, i.e. the still remaining large pores with a good continuity. Probably the untilled soil was composed of a system of densely packed aggregates with small pores, which primarily determined penetration resistance, and of a sparse and more or less continuous system of medium-sized and large pores. Roots grow easily in the part of the system with pore necks not smaller than the root diameter. Roots can slowly penetrate the somewhat smaller necks only when the resistance of the soil mass is not too high. Lateral roots are clearly thinner than primary roots, like the taproot of sugar beet. Consequently, for unimpeded root growth smaller pores would suffice. However, these laterals develop at arbitrary places along the primary root axes. Therefore, for many of these laterals the chances are high of encountering a high mechanical resistance, which reduces the possibility for root growth. Planes of weakness between the aggregates developed by shrinking and swelling processes, could also offer some possibilities for the root system. The dry, massive, untilled soil mass could be broken in sharp-edged aggregates, but sometimes even in the field when the soil was in a friable condition. Moreover, at several occasions, concentrations of sugar beet roots on aggregate surfaces have been observed. Nevertheless, it is still likely that, due to insufficient pore continuity, a significant part of the pore system cannot be used by the root system. As a consequence, in untilled soil, the rootable pore system will be rather sparse. However, because the pore system is rather permanent, there is a real chance that especially the easiest rootable part of the system will be used again by the root systems of subsequent crops. Indeed, at several occasions, in some of the large pores, living roots as well as partly decayed roots of a previous crop were found.

Soil structure changed tremendously at the transition from the loose ploughed soil to the dense ploughpan. It can be expected that in the soil that had not been tilled for eight years pore continuity at this transition will be greater (Goss et al., 1982). In 1978, for spring barley this transition was a temporary barrier for the expansion of the root system, especially in ploughed soil. However, the limited number of observations of the root system did not allow us to draw such a conclusion for sugar beet. In 1979, in both systems root expansion was hampered seriously by the ploughpan, but only in the ploughed soil roots accumulated just above the ploughpan. Nevertheless, in both years greater depths in the C horizon were reached at about the same date in both systems. Therefore, it can be concluded that, with respect to root growth, during the eight years of the experiment the soil structure of the ploughpan had not improved very much. This is also supported by the observation that once the roots had reached the undisturbed spongy structure of the subsoil root growth to depth accelerated again. In 1979 this occurred even though the mean O.D.R. was insufficient. Obviously aeration within the vertical continuous medium-sized pores was greater than in the more or less homogeneous soil between these pores.

In the untilled soil, the amount of roots in the arable layer decreased very sharply with depth, whereas in ploughed soil, in general, the root distribution was more uniform. With maize this phenomenon could be explained, irrespective of the level of nutrients, by a higher mechanical resistance in untilled soil (Boone & Veen, 1982). Therefore, probably with sugar beet the higher mechanical resistance was also the principal factor, whereas an uneven distribution of nutrients (Chapter 5) or, in 1979, a temporarily insufficient aeration, only strengthen this effect.

In untilled soil during the second and third wet period of the 1979 growing season, aeration temporarily dropped below critical levels. As a result, in untilled soil, for some time the leaves of the small sugar beet plants yellowed more than in tilled soil. A totally insufficient aeration, which stopped root growth and ion uptake during the periods when the soil was nearly waterlogged, has to be considered as the primary factor. At slightly decreased soil water potentials, aeration in untilled soil was still insufficient in many spots. The maximum mechanical pressure the root can exert in these spots will be diminished when the expanding root tip has to deal with a shortage of oxygen (Gill, 1956). In the previously described model of the pore system, at more negative soil water potentials, a decreasing proportion of the root system is surrounded by a saturated or nearly saturated soil-water complex. In this situation both mechanical resistance and insufficient aeration will diminish root growth. In 1979, when insufficient aeration had no permanent detrimental effects, evapotranspiration gradually decreased soil water content and improved aeration. However, at the same time, mechanical resistance increased and, therefore, during a prolonged period of time the total number of roots in the arable layer was smaller than in ploughed soil.

In a homogeneous soil (physical) environment, every spot has the same rootability. In a heterogeneous soil (physical) environment, rootability depends on the spot concerned. The absolute differences in rootablility between different spots and the dimensions of these spots determine the degree of heterogeneity in rootability. Under similar conditions, actual differences in root growth between different spots, however, are greater than can be expected from the differences in rootablility (Boone, unpublished results). The principle of preferential root growth is also applicable when there is a difference in rootability between different soil layers. Although the results obtained with sugar beet are less convincing than those obtained with spring barley, generally, more roots were found in the seedbed of the untilled soil than in the seedbed of the ploughed soil. Irrespective of nutrient level this could be explained by differences in mechanical resistance of the soil below the seedbed (Boone & Veen, 1982). Nevertheless, higher availability of nutrients and water in the seedbed of the untilled soil may have contributed.

The undisturbed spongy structure below the ploughpan had a better rootability than the ploughpan, but it was still considerably lower than in the ploughed arable layer with its very heterogenous pore size distribution. Consequently, the soil profile of System A was composed of an arable layer with a high rootability, a ploughpan with a low rootability and a subsoil with a medium rootablilty. System B1 was composed of an arable layer with a medium-low rootability, a ploughpan with a low rootability and a subsoil with a medium rootability. The concept of preferential root growth predicts that the untilled soil should have more roots in the subsoil than the tilled soil. The data obtained with sugar beet in 1978 are too limited to draw a conclusion. In the beginning of August 1979 in the subsoil of untilled soil, indeed, more roots, in an absolute sense as well as relatively to the amount of roots in the topsoil, were found than in the subsoil of tilled soil. In late August, however, in untilled soil a smaller absolute and a similar relative number was found.

Accumulation of roots above the ploughpan of the ploughed soil was more pronounced in the middle between crop rows than in the crop rows. Below the ploughpan more roots were found in the crop rows than in the middle between the crop rows. This may be explained by the results of Dexter (1978). He demonstrated that the smaller the angle of approach of a root to a transition between regions with different mechanical impedance, the smaller the chance that the root will penetrate.

In both years emergence in System B1 was slightly better and plant density more regular than in System A. However, early shoot growth was quite different between years. In 1978, early shoot growth was better on untilled than on ploughed soil. This may be explained by the much higher root density and the higher concentration of phosphate and potassium in and directly below the seedbed (Chapter 5), or by a greater availability of water due to a better root-soil contact or by a greater capillarity in the dense untilled soil below the seedbed. However, deeper in the arable layer root density was clearly lower in untilled than ploughed soil. In June, with a high evapotranspiration and a low amount of rainfall, the top layer dried out and shoot growth therefore lagged clearly behind. Nevertheless, the untilled soil had a higher shoot weight per hectare, because plant density was considerably higher than on ploughed soil. At that moment taproot development of the sugar beet showed the same tendencies. Taproots on untilled soil were smaller, especially shorter and the number of fanged roots was considerably higher than on ploughed soil. In July it became clear that on untilled soil, shoot growth was less depressed than taproot growth. In the meantime the root system on both tilled and untilled soil started to exploit the subsoil in a similar way. Because the growing season was favourable, taproot growth between mid-July and harvest in November was strong and similar on both systems. Final taproot and sugar yields were high and, with an adequate nitrogen fertilization, similar on both untilled and ploughed soil.

In 1979, shoot and taproot growth started at a lower rate than in 1978. This was related to a higher rainfall and a lower evapotranspiration. During two wet periods, at the end of May and mid-June, aeration on untilled soil was temporarily insufficient. Therefore on untilled soil early shoot and taproot growth was considerably smaller than on ploughed soil. Shoot growth was slightly less depressed than taproot growth. Later in the growing season differences in plant growth between untilled and ploughed soil gradually decreased and were even partly compensated. Shoot growth, however, recovered much earlier than taproot growth. In July, shoot growth on untilled soil was already larger than on ploughed soil. This coincided with the moment that the root system had passed the ploughpan and started to exploit the subsoil. As long as the roots were restricted to the untilled arable layer, root functions did not fully meet potential shoot growth. Differences between systems in shoot weight had nearly disappeared by the end of August, but differences between systems in taproot weight still had increased and amounted to 11 t ha^{-1}. Taproots on untilled soil were considerably shorter and more fanged than on ploughed soil. However, after the end of August on untilled soil, taproot weight increased much more than on ploughed soil. As a result of this compensation, on untilled soil final root yield in November was only 10% and maximum sugar yield 13%

smaller than on ploughed soil. On untilled soil high nitrogen applications could not prevent this smaller yield.

In 1978, with an adapted management, similar sugar yields could be obtained on untilled and ploughed soil. In 1979, however, yields on untilled soil were, despite a higher plant density and higher nitrogen fertilization significantly smaller than on ploughed soil. Therefore, untilled soil is not very attractive for sugar beet growing. Moreover, it should be emphasized that this experiment was conducted on a fertile, well drained, stable and permeable soil under temperate conditions. If, when tillage is omitted, a less heterogeneous soil structure had resulted, it can be expected that even poorer yields would have been obtained.

9.5 Conclusions

1. On untilled soil, a seedbed of sufficient quality for sugar beet could be prepared in time by harrowing the soil time before seedbed preparation, which improved superficial soil drying, and a very intensive seedbed preparation with a full-width rotary cultivator. In 1978 and 1979, on untilled soil, emergence was slightly better and plant density more regular than on ploughed soil.

2. The surface of the fine sugar beet seedbed on top of the dense untilled soil easily slaked. At heavy rainfall this caused run-off and waterponding in dips. However the hard crust, which developed at drying, proved to be a more serious potential risk for emerging sugar beet seedlings than insufficient aeration.

3. In the 1978 and 1979 growing seasons, neither the untilled arable layer nor the ploughpan formed a serious barrier for transport of water. When there were no large differences in root density and water uptake, soil water potentials were similar in both tilled and untilled soil.

4. When the soil was at field capacity (soil water potential of – 10 kPa) aeration in both the tilled and untilled arable layer was sufficient (mean O.D.R. $>20\ 10^{8}$ g cm^{2} min^{1}). At soil water potentials less negative than about – 3 kPa, which were observed in spring for some time during prolonged or heavy rainfall, aeration was still sufficient in the ploughed soil but insufficient in the untilled soil.

5. In 1978, during root development of sugar beet, aeration in both the tilled and untilled arable layer was sufficient. Observed differences in root growth between systems, therefore have to be ascribed to differences in soil mechanical resistance. In 1979, due to a much higher amount of rainfall in May and June, both differences in mechanical resistance and aeration were responsible for differences in root growth between systems.

6. The mean oxygen diffusion rate (O.D.R.) in the ploughed arable layer will be insufficient only at very high soil water potentials close to saturation. Under the conditions studied this situation was very rare. In the untilled arable layer critical O.D.R. values were obtained at soil water potentials less negative than – 3 kPa and in the ploughpan of both systems already at – 7 kPa. In the wet 1979 growing season, in the ploughpan of plots with sugar beet, a sufficient O.D.R. was reached earlier in loose-soil husbandry than in the no-tillage system. Probably this was caused by a faster developing root system and a higher rate of water uptake in the ploughed than in the untilled soil in the zone just above the ploughpan.

7. In both years root growth to depth of the sugar beet crop in the arable layer

proceeded when the soil was at about field capacity and penetration resistance amounted to 2 – 3 MPa in untilled and to 1 – 1.5 MPa in tilled soil. In 1978 root branching occurred at lower water contents and, therefore, at clearly higher penetration resistances. In 1979, soil water contents remained high for a longer period of time, and for more than one month the root system developed at intermediate high penetration resistances.

8. The penetration resistance of the ploughpan was always somewhat higher in loose-soil husbandry than in the no-tillage system, because in loose-soil husbandry the ploughpan was slightly stronger developed. Moreover, in the early 1979 growing season, due to a higher root density of the sugar beet crop in the lower part of the arable layer, soil water content of the ploughpan decreased somewhat earlier than in the no-tillage system.

9. In the arable layer, root growth of sugar beet to depth was only slightly faster in ploughed than in untilled soil. This supports the concept that untilled soil was composed of a system of densely packed aggregates, which primarily determined penetration resistance, and a sparse but more or less continuous system of pores with dimensions at least similar to those of sugar beet roots.

10. In the untilled arable layer, the number of sugar beet roots decreased very sharply with depth, whereas in the ploughed soil the root distribution was, in general, more uniform. Probably the higher mechanical resistance in untilled soil was the principal factor and the uneven distribution of nutrients or, in 1979, the temporary insufficient aeration only strengthened this effect.

11. During eight years of no-tillage, the rootability of the ploughpan was not much improved. The impression was gained that the ploughpan impeded root growth of sugar beet more under wet (1979) than under drier (1978) soil conditions. In the undisturbed spongy structure of the subsoil rootability was better than in the dense ploughpan.

12. Root growth of sugar beet in the subsoil was slightly better under no-tillage than under ploughed soil. This is in accord with the concept of preferential growth of roots. This implies that root growth in a certain soil layer is increased when the possibility for root growth in another layer with growing roots is decreased. However the results obtained with sugar beet were less convincing than those obtained with spring barley.

13. In 1978, early shoot growth of the sugar beet was clearly better on untilled than on ploughed soil. However in the subsequent relatively dry period, on untilled soil, shoot growth and especially taproot growth lagged behind, due to a more superficial root system. In the wet early growing season of 1979, shoot and especially taproot growth were always considerably less on untilled than on ploughed soil.

14. In 1978, about 2 months after shoot emergence, when the root systems of both tilled and untilled soil started to exploit the subsoil, shoot and taproot fresh weight of sugar beet in untilled soil were about 90 and 80%, respectively, of those in ploughed soil. However, in 1979, at the same time, shoot and taproot fresh weight in untilled soil were only about 65 and 60%, respectively, of those in ploughed soil.

15. In 1978, after the root systems of both ploughed and untilled soil started to exploit the subsoil, taproot growth of sugar beet was similar in both systems. At the same time in 1979, shoot growth sharply increased on untilled soil and was even stronger than on ploughed soil. Taproot growth recovered at considerably slower rate than shoot growth, but between the end of August and final harvest in November, taproot weight increased much more on untilled than on ploughed soil.

16. In 1978, final taproot and sugar yields were high. With a higher nitrogen fertilization, yields on untilled soil were about the same as on ploughed soil. In 1979, yield levels of sugar beet were clearly smaller than in 1978. On untilled soil, despite high nitrogen applications and compensational growth in the last months of the growing season, final taproot and sugar yields were smaller by about 10 and 13%, respectively, than on ploughed soil.

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10 Control of weeds, diseases and pests, and treatment of mulch

W.A.P. Bakermans & C. Vader

10.1 Weed control

As in previous years, intensive chemical weed control corresponding to modern agricultural practice was applied similarly in all tillage systems (Table 90). The results can be summarized as follows.

In potatoes, weed control was usually sufficient in all systems. In drought periods, however, in System B1 more annual weeds remained, and in System A sometimes many volunteer potatoes also remained. Also in winter wheat, the common weed control was usually sufficient; In System B2 sometimes additional control of *Matricaria chamomilla* was required. In sugar beet, System B1 had more annual weeds, which required one or more additional post-emergence sprayings. In this system more perennial weeds also occurred, which were weeded by hand in all systems. In spring barley, more annual weeds occurred in both Systems B1 and B2, sometimes requiring an additional spraying. In grass seed no weed control was usually necessary, due to severe crop competition, in the year the crop was harvested. In field beans, the soil herbicide was effective when the soil was sufficiently wet in spring. Under dry conditions an additional application of bentazon was required.

In the course of the growing season, weed coverage was evaluated a few times. The result was dependent on the time of evaluation. For instance, in the beginning of May the potato and sugar beet fields were still weed-free, whereas in the cereal crops many weeds were emerging. A representative example of the situation in spring barley before chemical weed control was applied is given in Table 91. Here distinctly more perennial weeds occurred in System B1 than in all other systems. System B2 even was free from perennial weeds on this date. System B1 also had most annual weeds, mainly because of the frequent occurrence of *Chenopodium album*. *Galium aparine*, however, was most frequent in System B2. By applying the herbicides mentioned in Table 90 these weeds could be controlled effectively, although in Systems B1 and B2 an additional spraying sometimes was required.

In all four years the weed evaluations of October showed the same overall picture. Due to the often more uneven stand of the crop in Systems B1 and B2, the average weed coverage was somewhat higher than in Systems A and C (Table 92). On the contrary, grass seed and field beans were a favourable exception. Due to careful weed control, weed coverage always remained below the level of damage in all crops.

In the autumns of 1977, 1978 and 1979 complete (whole field = 1500 m^2) weed surveys were made. The frequency of occurrence of each weed was separately recorded. From the large tables obtained in this way, no conclusions could be drawn about possible changes in the weed population with time: the different years showed roughly the same trends. In

Table 90. Herbicide treatments (1 unit = 1 kg ha^{-1} active ingredient)

Potatoes	Winter wheat	Sugar beet	Spring barley	Field beans	Grass Seed
Tillage Systems A, B1, B2 and C				*B2 only*	*B2 only*
After planting: 0.7 metribuzin (1976, 1978 and 1979) or 1 terbutryn/0.5 terbutylazin (1977). When necessary: additional handweeding	After sowing: 2.8 methabenzthiazuron (1976, 1977) or 0.61 linuron/2.28 nitrofen (1978, 1979). End of April: incidentally 4 DNOC or 1.92 bentazon (against Matricaria chamomilla). Beginning of May: 1.6 MCPA+2.1 MCPP End of May: repeated 1.2 MCPA. Mid-September: on grass as green manure crop 2.5 2.4-D + 2.4 MCPA.	After sowing: 2.6 pyrazon. May/June: once or repeatedly 1 fenmedifam application in the row on A and C; overall application on B1.	April/May: 6 DNOC. End of May: 1.2 MCPA + 1.6 MCPP; incidentally 1.92 bentazon. Beginning of June: incidentally 1.6 MCPA. Mid-September: on grass as green manure crop: 1 2.4-D/0.48 dicamba or 1.6 MCPA + 2.5 2.4-D	Before sowing: 0.4 paraquat + 0.4 diquat. After sowing: 0.4 simazin. Post emergence: incidentally 1.92 bentazon. After harvest: 3.6 2.4-D/0.72 dicamba	Grass under cover-crop and in stubble: see barley and winter wheat. Mid-September: after harvest of the cover-crop: 3.6 2.4-D 0.72 dicamba or 2.4 MCPA + 2.5 2.4-D. Mid-September: (to control volunteer barley) 0.88 endothalnatrium + 1 Citowett. Incidentally against Poa annua: 2.8 methabenzthiazuron. In 2nd year in dense stand of grass usually no chemical weedcontrol necessary
Additional on B1 and B2 weed and crop killing instead of tillage					
October: incidentally 1 paraquat	Beginning of October: killing of grass green manure 2.16 glyfosate Mid-March: incidentally 0.6 paraquat	March: incidentally to control regrowth of beet-tops on C and B1 and to kill emerged weeds 0.4 paraquat + 0.4 diquat	Beginning of October: killing of grass green manure crop on B1 2.16 glyfosate	Beginning of October: 2.16 glyfosate	Mid-September: 2.16 glyfosate Incidentally before sowing winter wheat: 0.4 paraquat + 0.4 diquat

Table 91. Proportion (%) of the soil surface covered by weeds in spring barley, 15/5/1978.

Weeds	A	B1	B2	C	Mean
Perennial					
Cirsium and *Sonchus* sp.	1.0	2.5	0.0	3.0	1.6
Tussilago farfara	1.0	0.5	0.0	0.5	0.5
Polygonum amphibium	0.0	4.5	0.0	0.0	1.1
Mean	0.7	2.5	0.0	1.2	1.1
Annual					
Veronica sp.	0.5	1.0	0.5	0.0	0.5
Matricaria chamomilla	1.0	1.5	1.5	1.5	1.4
Galium aparine	2.5	3.0	6.5	3.0	3.8
Stellaria media	1.0	1.5	1.5	1.5	1.4
Chenopodium album	0.5	9.0	0.5	1.0	2.8
Polygonum convolvulus	1.5	1.5	0.0	1.5	1.1
Various weeds	1.5	1.5	1.0	1.5	1.4
Mean	1.2	2.7	1.7	1.4	1.8

Table 92. Visual estimation of weed coverage in October, averaged over the years 1976 - 1979[a].

Crop	Tillage system				Mean
	A	B1	B2	C	
Potatoes	7.8	6.6	–	7.6	7.5
Grass seed	–	–	8.1	-	
Sugar beet	7.9	7.3	–	8.4	7.9
Field beans	–	–	7.9		
Winter wheat	8.3	7.3	6.8	8.7	7.8
Spring barley	8.0	6.4	6.4	7.7	7.1
Mean					
Cereals	8.2	6.8	6.6	8.2	7.4
Root crops	7.8	7.0	–	8.0	7.6

a. 10 = weed free, 5 = rather many weeds, but below the level of damage.

the grass seed, distinctly fewer species were found than in the other crops (Table 93). The root crops contained some more weed species than the cereal crops. The differences between the soil tillage systems were negligible. It is also interesting to note that, after cereals, on average the number of weed species was the same in all systems (Table 93), whereas the weed coverage of the B systems was distinctly higher (Table 92).

The number of times a frequent weed species was observed has been given as a frequency percentage in Table 94. A percentage of 100 means that the species was found at least once in all observations in each field of the relevant system; 25% means the species was only found in a quarter of the observations per system. For many weed species, observations were rare as only a few plants of each were sighted. These rare species are not considered here. The frequency percentages show that even the frequently present

Table 93. Number of weed species observed in autumn, averaged over the years 1977 - 1979.

Crop	Tillage system				Mean
	A	B1	B2	C	
Potatoes	25	26	–	24	25
Grass seed			8		
Sugar beet	25	20	–	20	22
Field beans	–		15	–	
Winter wheat	18	18	18	15	17
Spring barley	18	19	18	18	18
Mean					
Cereals	18	18	18	17	18
Root crops	25	23	-	22	23

Table 94. Frequency (%) of some frequently present weed species in the autumn (average for 1977, 1978 and 1979).

Weeds	Tillage system				Mean
	A	B1	B2	C	
Perennial					
Cirsium arvense	35	65	40	40	45
Sonchus arvensis	48	54	54	46	50
Equisetum arvense	37	31	17	35	30
Tussilago farfara	42	40	8	42	33
Elytrigia repens	15	8	6	31	15
Polygonum amphibium	19	46	8	12	21
Mean	33	41	22	34	32
Annual					
Mentha arvensis	40	31	8	33	28
Veronica sp.	58	54	83	46	60
Lamium purpureum	29	33	31	27	30
Matricaria chamomilla	56	44	60	40	50
Galium aparine	46	67	50	42	51
Senecio vulgaris	42	50	46	40	44
Stellaria media	50	27	42	50	42
Polygonum persicaria	12	33	6	8	15
Euphorbia peplus	33	25	19	27	26
Poa annua	21	27	48	21	29
Polygonum convolvulus	54	56	23	52	46
Mean	40	41	37	35	38

weed species were often absent despite the total size of the fields evaluated (1500 m^2). The general impression was that total weed coverage remained below the level of damage.

In System B1 distinctly more perennial weeds were present than in the other treatments, especially *Cirsium arvense, Sonchus arvensis* and *Polygonum amphibium* occurred frequently. System B2 however, showed less perennial weeds than Systems A and C with the exception of *Sonchus arvensis*. Especially *Equisetum arvense, Tussilago* *farfara, Elytrigia repens* and *Polygonum amphibium* only occurred at low frequencies. The different crop rotation, especially the grass seed crop, and herbicide application in System B2 were apparently favourable in the control of these weeds. In the B1 and B2 fields, *Elitrigygia repens* (couch grass) showed a low frequency. The additional control of this weed by hand spraying was evidently successful. On average, the frequency of perennial weeds in System A was almost equal to that in System C. However, it was striking that in System C *Elytrigia repens* occurred relatively frequently and *Polygonum amphibium* only rarely.

The average frequency of annual weeds dit not differ much between tillage systems. In System B2, *Mentha arvensis, Polygonum persicaria, Polygonum convolvulus* and *Euphorbia peplus* occurred relatively infrequently and *Veronica* spec., *Matricaria chamomilla* and *Poa annua* relatively frequently. System B1 had little *Stellaria media* and relatively much *Galium aparine, Senecio vulgaris* and *Polygonum persicaria.* Nearly all annual weeds were found somewhat less frequent in the C plots than in the A plots.

Before sowing cereals, sometimes an additional treatment with paraquat or diquat was required, and sometimes in the standing crop additional treatment with bentazon or MCPA was necessary. In sugar beet always an additional treatment with phenmedipham was required and perennial weeds had to be additionally hand weeded.

In accordance with other experiments, to control weeds (especially couch grass and other perennials) and to kill green crops in autumn, application of glyfosate was more effective than paraquat and diquat.

10.2 Diseases and pests

The same intensive control of diseases and pests as in the preceding years was applied in all tillage systems (Table 95). In this way damage caused by diseases and pests could be adequately prevented. Perhaps because of this chemical control, no distinct differences were found in the incidence of diseases and pests between the different tillage systems. However, in 1977, when winter wheat was growing abundantly, somewhat more mildew

Table 95. Chemical control of diseases and pests (1 unit = 1 kg ha^{-1} active ingredient).

Potatoes	Against phytophthora according to requirement 8 to 10 times 1.2 maneb/0.24 fentinacetate. The first time 2.1 zineb. Mid-June: 0.25 pirimicarb against aphids.
Winter wheat	In stage 5: 1.0 chloormequat against lodging. Just before flowering: 2 maneb/0.24 carbendazim. If necessary: 0.25 pirimicarb against aphids (once in 1976 and twice in 1979).
Sugar beet	Seed treatment against fungi and soil insects; in 1976 – 1978 with methiocarb, in 1979 with bendiocarb. In 1977 – 1978 1.5 aldicarb against Heterodera sp. In May 1978 and '79 0.5 parathion against mangold beetles. May/June 1976, 1977 and 1979: 0.25 pirimicarb against aphids.
Spring barley	No treatment necessary.
Grass seed	No treatment necessary. According to requirement: crimidine-baits against mice.
Field beans	According to requirement: 0.25 pirimicarb against Aphis fabae.

and yellow rust were found in System A. As also mentioned in Chapter 11, animals such as mice, pigeons, pheasants and slugs felt at home on the mulch-covered soil and they sometimes caused damage. The occurrence of *Heterodera* spec. was strikingly lower at the end of the rotation in the non-tilled than in the tilled soil.

10.3 Treatment of mulch

The intention was to leave in all systems the same, maximum amount, of organic matter. The organic matter consisted of plant remains (cereal straw, potato foliage, sugar beet tops and leaves) and green manure. Perennial ryegrass was grown for green manure with cereals as a cover crop. The combine harvester chopped the cereal straw and distributed it, so that it did not hamper the development of the green manure grass crop. On the tilled soil ploughing in this mulch was generally not difficult, even if the chopped straw was distributed rather irregularly.

To provide a good seedbed for potatoes on the non-tilled soil, before planting the rather thick layer of mulch (in March some 3500 – 5000 kg ha^{-1} of dry matter still remained on the soil) was intensively mixed with the soil by means of a rotavator. At the same time the grasses and weeds present were completely destroyed. Since the top of the non-tilled soil dried less rapidly under the mulch, in 1977 the potatoes had to be planted one month later in this system. Therefore, in 1978 and 1979 the mulch layer on the non-tilled soil was harrowed lightly before planting, so that the soil dried somewhat better and the potatoes could be planted at the same time as in Systems A and C.

Experience in the first crop rotation had shown that sugar beet emergence was hampered by too much straw mulch. Therefore in 1976 and 1977, winter wheat straw was removed. However, in 1978 and 1979, when the soil was harrowed before seedbed preparation, straw removal was no longer necessary. For field beans, too, winter wheat straw was removed in 1976 and 1977 but not in 1978 and 1979.

In System B2 a considerable layer of mulch of the preceding field beans was often still present at the moment of sowing spring barley. At sowing with the no-tillage seeder in System B2, 20 – 30% more seed was used than in the other systems, and usually equal numbers of plants were counted (Chapter 7).

In System B2 some more winter wheat seed was also used when sowing in the stubble of the grass seed crop. In addition, it was not only necessary to remove the grass straw, but usually the remaining stubble of the grass seed crop had to be burned. In 1976 about 5000 kg ha^{-1} dry matter remained on the soil, in 1977 this was 2600 kg ha^{-1} and in 1978 over 4000 kg ha^{-1}. With these amounts the soil between the rows of grass was lightly covered, whereas in the grass rows the amount was twice as high. After burning this heavy stubble the seed could be sown well with the no-tillage seeder and emergence was generally good. After burning, at some spots the soil remained almost bare without a mulch cover. In these places soil slaking occurred easily, as, for instance, in 1976.

In System B1, usually the grass green manure crop sown under the cereals did not develop into a heavy crop after cereal harvest. The grass was killed with glyfosate in October, and in spring it was possible to prepare a reasonable seedbed for sugar beet with the rotavator. Since the top of the untilled soil dried less rapidly under the mulch, in 1976 and 1977 the seedbed could not be prepared in time. Therefore, the sugar beet were sown some weeks later than in the tilled soil.

At the time the field beans were sown in the mulch of the grass green manure crop, which usually was not too heavy, the soil of System B2 was rather wet. At the spots where little mulch had been left, especially between the grass rows, much soil adhered to the disks of the no-tillage seeder, which had almost the same effect as a superficial tillage. This diminished slaking in places where the soil was too bare and emergence was generally affected favourably. At places with more mulch the soil adhered less to the disks, but sowing went very well and emergence was also good. Only in the dense wheel tracks were emergence and seedling growth distinctly hampered.

10.4 Earthworm activity

In the autumn of 1979 the number of earthworm pores was counted after winter wheat and spring barley harvest to study the effect of soil tillage on the activity of earthworms. This was done by removing the soil to a depth of 5 and 25 cm. The countings were done in triplicate in sample sites of 0.04 m^2. While removing the soil, the number of live earthworms was recorded. A great number of small pores with a diameter of < 1.5 mm was found, which were mostly not from earthworms, and clearly wider pores (> 1.5 mm), which were mostly from earthworms. Although the separate observations varied widely, the average showed a distinct trend (Table 96). The soil in System B2 evidently contained more biopores (> 1.5 mm) than in Systems A and B1, both in the topsoil as well as at ploughpan depth. The soil in System B2 had not been disturbed for 8 years but the crop rotation had also been different. Because of the variability in the data, the number of biopores in the ploughpan does not seem to differ between Systems A and B1. At a depth of 5 cm, however, System B1 had three times as many biopores > 1.5 mm as System A. Probably, tillage needed for growing root crops in System B1, was already sufficient to seriously disturb the earthworm population, but in the year with a cereal crop the population could recover somewhat in the undisturbed topsoil.

10.5 Conclusions

1. In potatoes, winter wheat and spring barley, chemical weed control was successful in all tillage systems, but in Systems B1 and B2 in spring barley one or two additional applications of bentazon were usually necessary.

2. In sugar beet, chemical weed control by applications of pyrazon and phenmedipham was insufficient. In all tillage systems additional hoeing and hand weeding was necessary.

3. In the grass seed crop in System B2, due to heavy crop competition, no chemical weed control was necessary in the second year.

4. For weed control (especially couch grass and other perennials) and the killing of green crops in autumn, glyfosate was more effective than paraquat and diquat.

5. In the no-tillage plots the stand of the crops often was somewhat uneven, which favoured weed growth. Generally, weed control in untilled soil is more difficult and necessitates more herbicides than in tilled soil. With lapse of time no distinct changes in weed population were found.

6. In the no-tillage plots covered with mulch, apart from slightly less damage by mildew and slightly more damage by slugs, mice, pigeons and pheasants, no distinct

Table 96. Number of biopores and number of live earthworms per m^2 (10 October 1979).

Depth (cm)	Previous crop	System A			System B1			System B2		
		Biopores		Earthworms	Biopores		Earthworms	Biopores		Earthworms
		< 1.5 mm	> 1.5 mm		< 1.5 mm	> 1.5 mm		< 1.5 mm	> 1.5 mm	
5	Winter wheat	16	0	0	83	16	0	558	42	16
	Spring barley	17	8	0	75	8	0	475	92	67
	Mean	17	4	0	79	12	0	516	67	42
25	Winter wheat	8	8	0	142	16	0	283	67	33
	Spring barley	267	8	0	75	8	0	600	83	42
	Mean	137	8	0	108	12	0	442	75	38

differences were found in the incidence of diseases and pests with the other tillage systems. However, at the end of the rotation the occurrence of *Heterodera* sp. was strikingly lower on the non-tilled soil.

7. Plant remains protected the soil from slaking and, provided not too much material was left, also gave a better crop emergence.

8. On the no-tillage plots, emergence and seedling development were sometimes seriously hampered by a too large amount or a too irregular distribution of undecomposed organic material. Therefore, on the non-tilled soil, excessive amounts of mulch from a grass seed crop have been removed or burnt before sowing.

9. Non-tilled soil will dry slower in spring, especially when covered with a thick layer of mulch. To increase surface drying in System B1, the soil was lightly harrowed some weeks before preparing the seedbed. In System B2, sowing sometimes had to be postponed.

10. If in spring, 2000 kg of dry matter per ha of undecomposed material still remains, the sowing of sugar beet will be difficult and emergence will be hampered. Cereals, and grass tolerate considerably more mulch. Even with a good distribution, however, leaving $>$4000 kg of dry matter per ha of undecomposed matter as a mulch is not advisable.

11 No-tillage cropping with and without root crops

W.A.P. Bakermans & C. Vader

11.1 Introduction

The growing of root crops, especially potatoes, usually is associated with rather intensive tillage. In a rotation with root crops, 'pure' zero-tillage, in which no tillage whatsoever is applied, is impossible. Therefore a crop rotation without root crops was also included. The only tillage taking place in this system is that of the rotating sowing coulters, which make a V-shaped slot into which the seed is dropped.

For the best comparison of no-tillage with and without root crops, winter wheat and spring barley in the rotation with root crops (B1) and in the rotation without root crops (B2) were always grown in adjacent plots.

Since 1976, rotation B2 consisted of spring barley with undersown grass – grass seed – winter wheat with undersown grass – field beans. Therefore when comparing yields of spring barley and winter wheat with rotation B1 it should be borne in mind that yield differences may be due to the combined effect of crop rotation and soil tillage.

11.2. Winter wheat

In Chapter 7 it was shown that Systems A and C gave almost the same winter wheat yields. Indeed, some slaking of the soil occurred in System C, but this did not affect crop yield adversely. In contrast, soil slaking on the B plots in 1976 and 1978 was so severe that they had to be resown with spring wheat. In addition, ducks and pheasants caused severe damage; apparently, they were keener on seedlings of spring wheat than on seedlings of spring barley.

In November 1975 heavy rainfall just after sowing caused severe soil slaking and the winter wheat on the B plots failed completely. Because the grass seed stubble had been burned too bare, soil slaking in System B2 was even worse than in System B1. In the spring of 1976 more bird damage was done to the newly sown spring wheat in System B2 than in System B1. As a result, the 1976 grain yield was about 14% lower in System B2 than that in System B1 (Table 53; Figs. 34 and 35). The yield of spring wheat in System B1 was about 10% lower than in Systems A and C, where soil slaking did not occur. This difference of 10% is normal for spring wheat compared to winter wheat. The yield data fluctuate rather widely, but the trend in the yields at the annual N levels suggests that the yield of spring wheat in System B1 had attained its optimum at 160 kg ha^{-1}, whereas in System B2 even at 160 kg ha^{-1} the optimum was not reached. The perennial N levels also show the greater N requirement of the spring wheat in System B2 compared with System B1.

In 1977 the winter wheat in System B2 remained a light crop with a large N response.

The winter wheat crop in System B1 was distinctly heavier than that in System B2. Fig. 34 clearly shows the greater N requirement of the wheat in System B2 compared to that in System B1 by the trend in the yields at both annual and perennial N levels. In System B1 the yield was almost the same as in Systems A and C. At 0 and 40 kg ha^{-1} the yield in System B2 was distinctly lower than that in System B1; at higher dressings yields were similar.

Figs. 34 and 35 show that in 1978 the yield of System B2 was, in general, lower than that in System B1, but again the yield of B1 roughly equalled those of Systems A and C. Because of heavy rainfall just after sowing in the autumn of 1977, the soil slaked and many wheat plants were killed, especially in the B2 plots. After burning the grass seed stubble, little mulch was left on the B2 plots: on average about 2700 kg ha^{-1} of dry matter. In the grass rows, where rather much mulch remained, most of the wheat plants also remained, but between the grass rows and in dips the soil was almost bare and the crop had disappeared partly. Many plants also disappeared due to severe damage by birds, which felt at ease on the partly mulch-covered soil. The winter wheat crop in the B2 plots, was much too thin and was, therefore, reseeded with spring wheat. This spring wheat, which germinated well, was almost completely consumed by ducks and pheasants. The much too thin a crop in System B2, which was infested by weeds, yielded distinctly lower than the other systems. At the annual N levels, only the yield of System B2 with much nitrogen was again almost equal to those of Systems A, B1 and C.

In 1979 soil slaking in System B1 was worse than in System B2. In System B2 the large amount of (on average 4000 kg ha^{-1}) dry matter had a distinctly favourable effect, although in places with too much mulch the number of plants was somewhat lower. As in the other years, especially at the perennial N levels, the wheat in System b2 required more nitrogen. At the highest perennial N level, the yield of B2 was equal to those of Systems A and C. At the annual N levels the yields fluctuated rather irregularly. In the wheat crop of the non-tilled soil, in contrast to the tilled soil, even at the highest N level no lodging occurred.

11.3 Spring barley

In 1976, at the perennial N levels, the yields of spring barley were almost equal for Systems B1 and B2. With high N dressings the yields of the untilled soil were equal to those of the tilled soil on both annual and perennial N levels (Table 67; Figs. 40 and 41).

In 1977, because the no-tillage drill was not available in time and because of the rainy weather afterwards, the spring barley was sown one month later on the B2 plots than on the other treatments. Emergence was good but there was much damage by birds, mainly pheasants. The crop remained, therefore, thin and small. In System B1, in contrast to System B2, puddles were formed because of soil slaking, which caused some bare patches. Therefore at the perennial N levels, the yield of spring barley in System B1 was somewhat lower than in Systems A and C. However at the annual N levels with adequate N, they were the same. In both cases the yield in System B2 was considerably lower. Throughout the growing season the crop on the tilled soil was thriving better than on the non-tilled soil.

In 1978, the spring barley on the non-tilled soil gave about the same yields as on the tilled soil. Yields were low this year and the nitrogen effect was only small. In contrast to the barley on the tilled soil, the barley on the non-tilled soil did not lodge at all. System B2 evidently could endure more nitrogen than Systems A and C.

In 1979, the barley yield at the annual N levels was difficult to estimate because, due to the many detailed observations on soil structure and on crop response, several plots could not be harvested in the normal way. During heavy rainfall local puddles were temporarily formed, mostly in System B2. In addition, the heavy rainfall caused a sharp N response. The yields at the perennial N levels show that with sufficient N the same yields can be obtained on the non-tilled soil as on the tilled soil. From the annual N application, it appeared that the spring barley on the non-tilled soil again had a high N requirement, especially in System B2. While at the higher N levels much lodging occurred on the tilled soil, the crop on the no-tillage soil remained erect.

11.4 Field beans, grass seed and grass green manure

Since field beans and grass seed were only grown on the B2 plots, a comparison with B1 plots is not possible. When sowing the field beans in spring, the soil was usually so wet that much soil adhered to the coulters of the no-tillage drill. Consequently, a more or less light tillage of the soil occurred, which generally had a favourable effect on emergence. However, early growth of the crop often was slow. Especially the plants sown in the wheel tracks were initially retarded. Nevertheless, the ultimate crop development was good. The seed yields in 1976 – 1979 were, 3.3, 5.5, 5.1 and 5 t ha^{-1}, respectively.

As in the previous rotation (1972 – 1975), the grass seed crop seemed especially suited for zero-tillage cropping. The perennial ryegrass could be sown well together with the spring barley and emergence was good. Due to heavy mice damage and adverse harvesting conditions, yields of uncleaned seed were generally not high (1000 – 1200 kg ha^{-1}). In 1979, seed yield was extremely high (2300 kg ha^{-1}). Hay was harvested only in 1976 and 1979 (about 8000 kg ha^{-1}); in 1977 and 1978 the hay quality was bad and, therefore, it was burnt.

The grass green manure crop sown under spring barley was successfully sown together with the cover crop. With wheat the sowing of the grass green manure crop in spring was more difficult. In System B1, and especially in System B2, the seed was not brought sufficiently into the hard soil with a conventional seeder. The seed had to be harrowed into the soil afterwards. In periods of drought, emergence and first growth were distinctly slower than on the tilled soil. However, the grass usually took advantage of the somewhat less abundant growth of the cover crop on the non-tilled soil. In general a good, not too heavy, grass green manure crop was obtained in all tillage systems.

11.5 Root crops

On the non-tilled soil potatoes and sugar beet were only grown on the B1 plots. Potatoes followed spring barley with a grass green manure crop of which the chopped straw was left in the field. As explained in Section 10.3, this caused no problems with mulching and chemical weed control. In Chapter 7, development was shown to be generally somewhat slower and the yield of saleable potatoes substantially lower than in Systems A and C. In System B1 there were considerably more green and malformed tubers.

Development of sugar beet generally was slower, beet yields and sugar contents were lower, harvest losses larger, and, therefore, the sugar yield considerably lower than on the tilled soil. Chemical weed control only, was neither successful.

11.6 Conclusions

1. With no-tillage systems, satisfactory results can only be obtained in rotations without root crops. The growing of root crops, especially sugar beet, seems unsuited to a system of sequential no-tillage.

2. In a rotation without root crops perennial ryegrass for seed production seems especially suitable for untilled soil. This suitability decreased somewhat in the order winter wheat, field beans and spring barley.

3. Cereals showed a greater nitrogen requirement in the rotation without root crops than in the rotation with root crops.

4. After root crops, before sowing into the bare soil, a seedbed should be prepared to prevent slaking of the non-tilled soil.

5. In a no-tillage system, mulch will prevent slaking of the soil. However, to prevent technical problems with sowing in the mulch and later with crop emergence, no more than about 4 t ha^{-1} of dry matter of plant remains should be left on the surface.

12 Emittance and reflectance characteristics

J.G. Lamers

12.1 Introduction

The emittance of an object is defined as the relative amount of emitted electromagnetic radiation. This emitted radiation depends on the thermal energy or temperature. At the surface of the earth the radiation is at maximum between 8 and 14 μm. Because the temperature of the sun is higher, the emitted radiation is at maximum in the visible part of the spectrum (0.4 - 0.7 μm). At the earth's surface therefore, the radiation in this wave band is dominated by the radiation of the sun. All or part of this radiation incident on the surface of an object is reflected. The mode and extent to which radiation is emitted or reflected by substances may give information about some characteristics of these substances. In this study airborne remote sensing was used to obtain information on the emittance and reflectance characteristics of differently tilled soil.

Soil characteristics, such as moisture content, pore space, clay and organic matter content, influence the heat and water balance at the surface in different ways. To be informed about the extent of these influences, simulation studies have been performed to simulate the temperature of the surface (Rosema, 1976). Temperature differences may be used as a soil characteristic. Temperature differences derived from thermal images made at sunrise may give more information about the thermal characteristics of the layers below the soil surface, as then differences in energy absorbed from the sun are absent (Janza, 1975). Also thermal inertia may be used as a soil characteristic. Thermal inertia is the rate of heat transfer at the interface between two dissimilar media. It can be estimated from the difference between maximum and minimum temperatures of the soil (Rosema, 1975). Compacted and moist clay soil will have a high thermal inertia and will give low differences between maximum and minimum temperatures.

Moisture content and soil roughness are related to soil texture and organic matter content. When moisture content and soil roughness decreased, reflectance in the visible and near infrared part of the spectrum increased (Janse and Bunnik, 1974).

After crop emergence, the average surface temperature is determined by the temperature of bare soil and vegetation. As vegetation transpires, surface temperatures may be far lower than the temperature of dry bare soil. When vegetation cover increases, the average surface temperature will decrease. A good relationship exists between the amount of vegetation and average surface temperature (Klaassen & Nieuwenhuis, 1978). With increasing biomass, reflectance in the red part of the spectrum decreases, whereas the reflectance sharply increases in the near infrared.

12.2 Materials and methods

This study was part of a project on the application of remote sensing techniques in agricultural research. The imagery was undertaken by the National Aerospace Laboratory (NLR) and sponsored by the National Remote Sensing Organisation (BCRS). Two remote sensing techniques were applied: thermal imagery, including thermal inertia, and false-colour photography, both performed from an aircraft which was flying at 500 m height in the South-North direction across the experimental field. A Reconofax VI thermal infrared analog linescanner and a TA-7M photocamera, to make 70 mm false-colour images, were assembled in the aircraft. Part of these images of the experimental field were transformed into slides.

For several plots of the experimental field the density of the transparant thermal films was measured with a Mac Beth transmission densitometer at the NLR; the slides were measured with the same apparatus at the Department of Surveying and Photogrammetry of the Wageningen Agricultural University. The thermal infrared films were corrected for the non-linear relationship between film density and the temperature recorded by the scanner (de Boer, 1973). The false-colour slides were measured with blue, green, red and yellow filters, which corresponds with reflectance in green, red, infrared and visible part of the spectrum, respectively.

Early in spring, bare soil dominates the scenery. Conditions for recording are optimal in the afternoon, at about 14.00 h, on a sunny day following a few dry days. Soil colour then changes from dark to light.

In spring 1979, heavy rains slaked the soil surface, especially on winter wheat fields. Slaked soil is characterised by a deterioration of aggregates, which results in a thin, compacted top-layer. The flight in the afternoon of 11 April 1979 was performed when the air temperature at 2 m above the soil surface was 17°C. The flight at dawn of 12 April 1979 was made after 3 – 4 mm of rain and a minimum air temperature of 7°C. The root crops were sown and planted later, so that on 19 June 1979 they did not cover the land completely. Therefore, surface temperature at that time was the average of the temperature of vegetation and bare soil. Air temperature was 23°C and since temperature variations at the surface were >4°C, two runs were flown, one with a low and one with a high setting of the remote sensing equipment.

On 12 April 1979, on all plots of two replicates of the experimental field soil samples were taken to determine the moisture content at 0 – 5 cm, 5 – 10 and 10 – 20 cm depths (L.M. Lumkes, PAGV). At 18 June 1979 the biomass of each crop was estimated. Data shown are the average of three nitrogen levels and three replicates (L.M. Lumkes, PAGV).

A statistical analysis of the results was made.

12.3 Results

12.3.1 Spring 1979

In the afternoon of 11 April 1979, between plots big differences in soil surface temperature were observed (Table 97; Fig. 90). In System B1, on plots where potatoes and sugar beet were to be grown, the cereal straw and grass green manure remained at the

Table 97. Soil surface temperature deviation (°C) from the overall mean value before spring cultivations in the afternoon of 11 April 1979.

1979 crop	Surface condition	A	C	BI	Mean
Potatoes	bare	-0.3	0.2[a]	1.4[a]	0.4
Winter wheat	thin crop	-0.2	0.7	0.5	0.5
Sugar beet	bare	-0.4	-0.2	1.7[a]	0.4
Spring barley	bare	-0.5	-0.2	0.3	0.3
Mean		0.4	-0.2	0.6	0

a. Cereal straw and grass green manure at the surface.

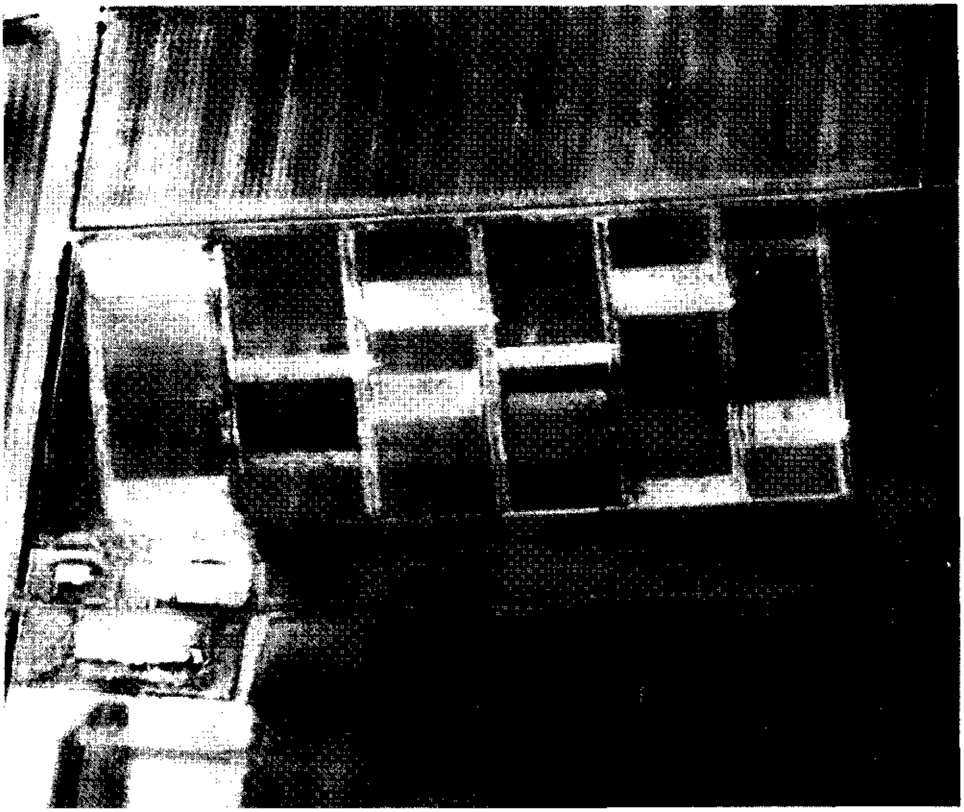

Fig. 90. Thermal image of the experimental field on 11 April 1979, showing dark features for low temperatures. Temperature range on the image is about 5°C. A plan of the field is shown in Fig. 98.

surface and, therefore, soil surface temperature of these plots was significantly higher – about 1.5°C above the overall average. In System C, the soil surface temperature of plots for potatoes after spring barley was about 0.9°C higher than for winter wheat after potatoes. For potatoes in System C, the soil was shallowly ploughed (15 cm) and crop debris of spring barley and grass green manure was not fully covered. Winter wheat after potatoes in System C have been slaked more severely, because the soil was cultivated with the fixed-tine cultivator instead of ploughed to 25 cm depth. Except for winter wheat, System A had an only slightly lower surface temperature than System C. Winter wheat and spring barley plots in System B2 had higher surface temperatures than in System B1 (Table 98), which was related to a heavier mulch of field bean straw and seed grass stubble.

The morning flight of 12 April 1979 showed much smaller temperature deviations (Tables 98 and 99; Fig. 91), but the same tendencies were observed as with the afternoon flight of the day before (Tables 97 and 98). During the night the soil had received a lot of energy from the atmosphere, because the atmosphere was unstable and some rain had fallen. Therefore, the surface did not cool enough and thermal inertia differences of the soil could not be found.

No-tillage with crop debris at the surface preceding potatoes and sugar beet (System B1), had a high soil moisture content in the 0 – 5 cm layer (Table 100). Thus, the isolating mulch layer resulted in a higher surface temperature (Table 99), but also in a much higher

Table 98. Soil surface temperature deviation (° C) from the overall mean value in Systems B1 and B2.

1979 crop	Surface condition	11 April 1979		12 April 1979	
		B1	B2	B1	B2
Winter wheat	thin crop	-0.5	-0.1	-0.2	0.1
Spring barley	bare soil	-0.3	0.8	-0.1	0.2

Table 99. Soil surface temperature deviation (°C) from the overall mean temperature in the morning of 12 April 1979.

1979 crop	Surface condition	A	C	B1	Mean
Potatoes	bare	-0.08	-0.01	0.40	0.10
Winter wheat	thin crop	-0.05	-0.12	-0.17	-0.11
Sugar beet	bare	-0.10	-0.06	0.43	0.09
Spring barley	bare	-0.10	-0.07	-0.06	-0.07
Mean		-0.08	-0.06	0.15	0

Table 100. Moisture content (%, w/w) of the 0 - 5 cm layer, 12 April 1979.

1979 crop	Surface condition	A	C	B1	Mean
Potatoes	bare	22.6	22.4	28.4	24.5
Sugar beet	bare	22.7	23.6	29.9	25.4
Spring barley	bare	21.8	24.4	26.2	24.1
Mean		22.4	23.5	28.2	24.7

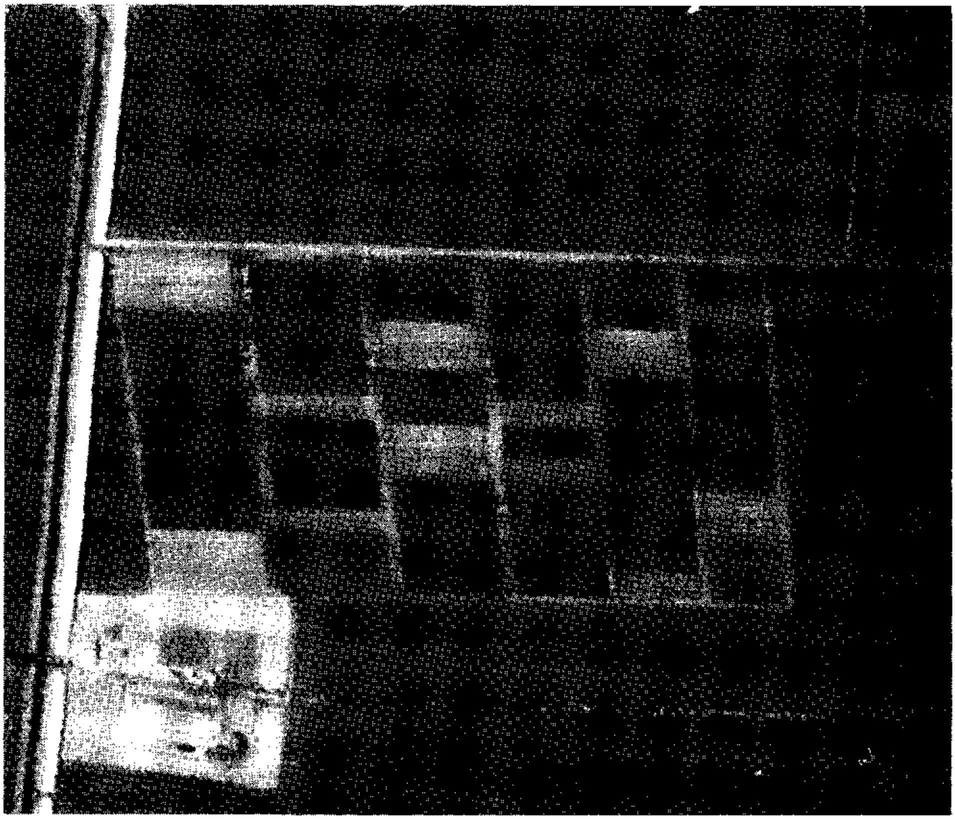

Fig. 91. Thermal image on 12 April 1979, showing dark features for low temperatures. Temperature range on the image is about 5°C. A plan of the field is shown in Fig. 98.

moisture content in the 0 – 5 cm layer. Therefore the common negative relationship between moisture content and surface temperature was positive. Between Systems A and C the small differences in surface temperature were not related to the small differences in moisture content in the 0 – 5 cm layer.

12.3.2 Summer 1979

On 19 June 1979, because of transpiration, surface temperatures on plots with winter wheat and spring barley were much lower than on plots with potatoes and sugar beet which were still poorly developed (Fig. 92). In Systems B1 and B2, where cereal crops failed due to soil slaking, open places with high temperatures were observed in one replicate with spring barley (Fig. 93) and in one replicate with winter wheat. On average, potatoes had the lowest temperatures in System A, whereas in System B1 temperatures were relatively high (Table 101; Fig. 92). Temperature variations within a plot were rather high, probably due to variation in biomass, in degree of soil slaking and the execution of field operations at the moment the flight was made.

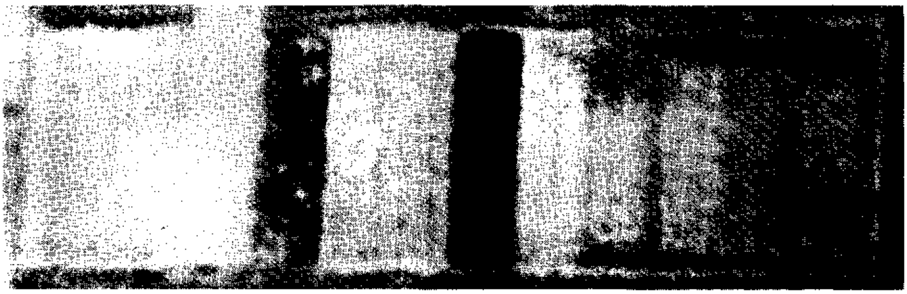

Fig. 92. Thermal image on 19 June 1979 with a temperature range of 5°C and a high mean temperature, Repetition II.

Table 101. Soil surface temperature deviation (° C) from the overall mean value, 19 June 1979 and estimates of biomass on 18 June 1979[a].

1979 crop	A	C	B1	Mean
Surface temperature				
Potatoes	-1.1	-0.3	0.3	-0.4
Sugar beet	0.3	0.3	0.6	0.4
Mean	-0.4	0	0.5	0
Biomass				
Potatoes	7.6	7.0	6.0	6.9
Sugar beet	6.0	5.5	3.8	5.1
mean	6.8	6.3	4.9	6.0

a. 1 = no vegetation; 10 = densely vegetated.

Visual estimation of crop stands on 18 June 1979 indicated for potatoes and sugar beet a decrease in biomass from System A via System C to System B1 (Table 101). As the

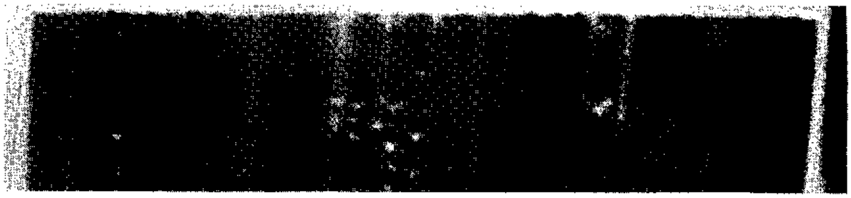

Fig. 93. Thermal image on 19 June 1979 with a setting of the remote sensing equipment giving a temperature range of 5°C and a low mean temperature, Repetition I.

temperature increased from System A via System C to System B1, temperature variations are probably caused by differences in biomass (Fig. 94).

The false-colour slides showed a rather constant variation in red density, whereas blue, green and yellow densities were highly correlated ($r>0.99$). Between tillage systems or between potatoes and sugar beet, differences in blue density were small (Table 102). On the slides the slaked spots in winter wheat and spring barley were clearly visible. The first replicate of sugar beet differed from the second replicate due to field operations being executed. Parallel dark and light diagonal stripes at about 14 m intervals could be seen. These were related to a former drainage system that causes small differences in relief and texture. For potatoes and sugar beet no relationship between the blue density and the temperature was found.

12.4 Discussion

The temperature of the surface of a bare soil depends on:
- the absorbed energy received from the sun or the atmosphere;

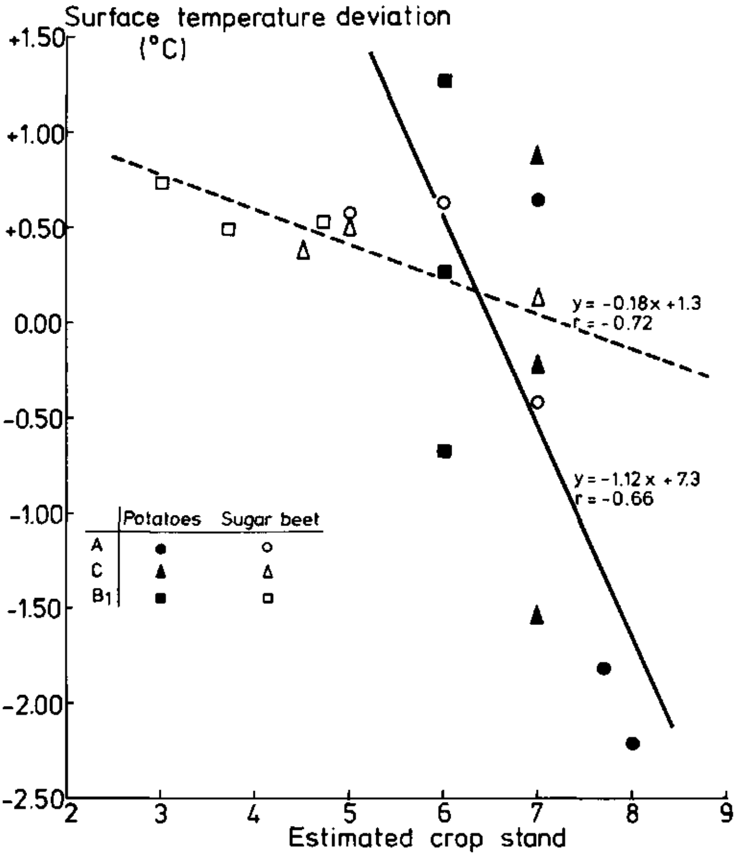

Fig. 94. Relation between estimated crop stand for potatoes and sugar beet, and soil surface temperature deviation from the overall mean for potatoes and sugar beet on 19 June 1979.

Table 102. Average blue density of the false-colour slide, 19 June 1979[a].

1979 crop	A	C	B1	Mean
Potatoes	2.00	2.05	2.08	2.04
Sugar beet	2.04	1.96	2.02	2.01
Mean	2.02	2.00	2.05	2.03

a. 0 = white; 3 = black.

- the transient and latent heat losses to the atmosphere;
- the heat loss to deeper soil layers depending on thermal conductivity and heat capacity of the soil.

According to Rosema (1976), who simulated the thermal behaviour of bare soils on the basis of heat and moisture transfer, small changes in pore space influence the moisture and transport characteristics, and thus the variation in soil surface temperature may be considerable. Pore space may be influenced by soil tillage to a depth of 25 cm (Chapter 3), but its influence on surface temperature is probably outweighed by the amount of crop debris at the surface. Debris dries quickly and forms an isolating layer on the surface, which decreases evaporation. When much energy from or through the atmosphere reaches the soil surface, tillage systems with much crop debris at the surface will have high surface temperatures, but also a high soil moisture content. Therefore, in 1979 the usual negative relationship between temperature and soil moisture content was not found.

Bijleveld (1977) showed that, because of differences in thermal inertia, sandy soils may be distinguished from clayey soils by subtracting minimum from maximum temperatures as obtained in morning and afternoon flights, especially in a situation of atmospheric stability. However, the morning flight of 12 April 1979 was made under unstable atmospheric conditions, so that no additional information could be obtained.

The most important reason for parallel stripes on thermal or false-colour images are differences in soil texture caused by the installation of a drainage system (Baltissen & Burrough, 1982). Indeed, on 11 and 12 April 1979, in the thermal image parallel stripes which were caused by a former drainage system, were seen across the experimental field.

Infrared photography may be used to estimate biomass. In 1979, only on 19 June were false-colour slides made. In the visible part of the spectrum they showed different features of tillage being executed (hoeing) and the former drainage system, but biomass differences on the slide were probably equalized by differences in soil condition. Relatively wet, dark places may have resulted in less developed crops.

Emittance and reflectance characteristics were highly influenced by soil surface conditions, such as the amount of crop debris and degree of slaking. Remote sensing of tillage systems may be done when tillage systems change these conditions in an unique way. For a sound interpretation of the images, 'ground truth' and knowledge of the various factors which influence the surface conditions are necessary.

12.5 Conclusions

1. To detect differences in emittance and reflectance characteristics of soil tillage systems in spring, thermal imagery and false-colour photography may, when performed in the afternoon of a sunny day, be useful for determination of soil surface temperature and reflectance.

2. Mulch in System B2 and crop debris in System B1 and System C after spring barley increased soil surface temperature.

3. Slaking of the soil in Systems B1 and B2, which resulted in open cereal crops, was easily detected in summer on both thermal and false-colour images.

4. Reduced growth of potatoes and sugar beet in Systems B1 and C resulted in higher surface temperatures than in System A, due to a small area of relatively cool biomass and a large area of relatively warm soil surface.

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13 Economical evaluation

H.Preuter

13.1 Introduction

The economical evaluation deals with the period 1976 - 1979 and is restricted to the crop rotation, including root crops, which consisted of potatoes - winter wheat - sugar beet - spring barley (Systems A, B1 and C). All these crops were present each year in triplicate per tillage system. The yield of these fields was determined at three perennial nitrogen levels: the normal rate of nitrogen (P), the normal rate minus 20% (P -) and the normal rate plus 20% (P +). The evaluation was based on the average yields during the second rotation at optimum nitrogen levels. The optimum yield and nitrogen rate result in the highest gross margin (gross output minus costs of nitrogen). In general, it appeared that for loose-soil husbandry and no-tillage the normal nitrogen rate plus 20% (P +) was optimal and for rational tillage the normal nitrogen rate (P). The optimum nitrogen rate for each soil tillage system is presented in Table 103.

13.2 Financial balance per crop

For each crop and each tillage system a financial balance was made, based on 1980 price and cost levels (Table 104). It consists of the gross returns, minus the variable costs, which include the costs of seed, fertilizer, plant protection products and interest.

It appears that on average the balance was highest in the case of 'rational' tillage (Dfl. 3 652). For loose-soil husbandry the balance was similar and for no-tillage it was much lower than for rational tillage, for potatoes by Dfl. 1 187, for sugar beet by Dfl. 933 and for grass green manure by Dfl. 373. On average the balance for cereals was a little higher because only in System B1 the straw is harvested as a by-product.

Table 103. Optimum nitrogen level for the main crops (kg ha^{-1}; 1976 - 1979).

Crop	Loose-soil husbandry (A)	No-tillage (B1)	Rational tillage (C)
Potatoes	295	295	248
Winter wheat	102	100	82
Sugar beet	193	200	157
Spring barley	65	62	40
Mean	164	164	132

Table 104. Physical yields, financial returns, variable costs and balance for the main crops and the undersown grass.

Crop	Yields (kg ha⁻¹)		Gross returns (Dfl. ha⁻¹)			Variable costs (Dfl. ha⁻¹)	Balance (Dfl. ha⁻¹)
	main prod.	by-prod.[a]	main prod.	by-prod.[a]	total		
Loose-soil husbandry (A)							
Potatoes	38750	7340	9688	440	10128	3274	6854
Winter wheat	6681	-	3207	-	3207	1007	2200
Grass green manure	-	-	-	-	-	294	-294
Sugar beet	9061	-	5890	-	5890	1849	4041
Spring barley	5135	-	2362	-	2362	386	1976
Grass green manure	-	-	-	-	-	270	-270
Mean	-	-	5287	110	5397	1770	3627
No-tillage (B1)							
Potatoes	33730	10730	8433	644	9077	3226	5851
Winter wheat	6187	4000	2970	280	3250	1010	2240
Grass green manure	-	-	-	-	-	744	-744
Sugar beet	7873	-	5117	-	5117	1896	3221
Spring barley	5109	-	2350	-	2350	380	1970
Grass green manure	-	-	-	-	-	733	-733
Mean	-	-	4718	231	4949	1997	2951
Rational tillage (C)							
Potatoes	39170	7700	9793	462	10255	3217	7038
Winter wheat	6515	-	3127	-	3127	968	2159
Grass green manure	-	-	-	-	-	294	-294
Sugar beet	9151	-	5948	-	5948	1794	4154
Spring barley	5087	-	2340	-	2340	347	1993
Grass green manure	-	-	-	-	-	443	-443
Mean	-	-	5302	116	5418	1766	3652

a. For potatoes: cullings; for winter wheat: straw (System B1 only).

13.3 Man-hours per ha when using own machinery

On the basis of the working width and capacity of the implements used, the task time has been calculated in man-hours per hectare. This calculation was based on data published in the PAGV Handbook on farm economics: Kwantitatieve Informatie 1980 - 1981 (Noordam & van der Ham, 1980). The task time is the time needed to carry out the operation, plus time for resting and personal care, defects, adjusting the machinery and transport. Always the best technical solutions were chosen which sometimes differed from those used in the present experiment. The average number of man-hours per ha was only slightly smaller in the case of loose-soil husbandry than with rational tillage but clearly higher in the case of no-tillage (Table 105). In loose-soil husbandry, more operations were combined at sowing and planting than in System C, but the time-saving aspect was less than expected. Although in no-tillage the main tillage operation was omitted, rotary cultivation for potatoes and sugar beet in spring required extra time as was the case for killing weeds and the grass green manure crop.

Table 105. Manhours per ha, using own machinery.

Operation	Loose-soil husbandry (A)	No-tillage (BI)	Rational tillage (C)
Potatoes			
Ploughing	2.1	–	1.5
Seedbed preparation	–[a]	4.2	0.5
Fertilization and spraying	6.0	6.0	6.0
Planting	2.5	2.0	2.0
Ridging	–[a]	2.5	2.5
Harvest and transport	14.8	14.8	14.8
Spring-tine cultivation	0.7	0.7	0.7
Total	26.1	30.2	28.0
Winter wheat			
Ploughing	2.1		
Fixed-tine cultivation	[a]		1.2
Sowing	–[a]	1.0	[a]
Fertilization and spraying	4.0	4.0	4.0
Harvest and transport	2.8	2.8	2.8
Baling and transport		2.1	
Total	8.9	9.9	8.0
Grass green manure sown under winter wheat			
Sowing and fertilization	1.5	1.5	1.5
Spraying	0.5	1.0	0.5
Total	2.0	2.5	2.0
Sugar beet			
Ploughing	2.1	–	2.1
Seedbed preparation	–[a]	4.7	0.5
Fertilization and spraying	3.5	3.5	3.5
Sowing	1.1	1.1	1.1
Hoeing and hand weeding	9.8	8.0	9.8
Harvest and transport	8.5	8.5	8.5
Spring-tine cultivation	0.7	0.7	0.7
Total	25.7	26.5	26.2
Spring barley			
Ploughing	2.1	–	–
Fixed-tine cultivation	–	–	1.2
Sowing, fertilization, seedbed prep. and spraying	2.0	2.0	2.0
Harvest and transport	2.8	2.8	2.8
Total	6.9	4.8	6.0
Grass green manure sown under spring barley			
Fertilization	0.5	0.5	0.5
Spraying	0.5	1.0	1.0
Total	1.0	1.5	1.5
Mean	17.7	18.9	17.9

a. Combination of operations.

13.4 Farm area, buildings, implements and labour

To assess the economic importance of soil tillage systems for a whole farm it is necessary to know the financial result of a particular farm. In our calculation the area of cultivated land was put at 36, 48, 60, 72, 84 and 96 ha, respectively, but the available labour of the farm was maintained at a minimum – one man. We have assumed that it was possible to engage casual labour for weeding, the necessity of which depends on the area of the crop concerned. For nearly all operations, calculations showed that it was more profitable to use the farmer's own machinery than to engage a contractor. The own machinery can be owned jointly with other farmers if that is less expensive or if it is necessary for the organisation of the work. It was assumed that a maximum of three farmers cooperate.

The labour supply for field operations was fixed at 80 h per half month per worker from April to October and 70 h for March and November. The replacement value of the buildings was put at Dfl. 425 per tonne of potatoes, at Dfl. 20 000 for the workshop and at Dfl. 250 m^{-2} for the implement shed.

13.5 Fixed costs

The costs of the land was fixed on the basis of lease with a rent of Dfl. 775 ha^{-1}. Maintenance costs of the drainage system was estimated at Dfl. 26 ha^{-1}. The paved field access road was calculated to have a length of 17 m ha^{-1}, with a replacement value of Dfl. 1700 ha^{-1}. Annual costs were put at 3% depreciation, 5% interest (10% of half the replacement value) and 1% maintenance. The same percentages were supposed to apply to the cost of parking implements. Annual costs of potato storage were fixed at 4% depreciation, 5% interest and 1% maintenance. Interest for implements was put at 6% (10% of 60% of the replacement value). The cost of fuel and lubricants was estimated at Dfl. 6 h^{-1}. Contractor's work not directly concerned with crop production, such as maintenance of ditches, was put at Dfl. 20 ha^{-1}. Total labour costs, including social charges, holiday bonus and remuneration of overtime were calculated at Dfl. 45 000 per worker and the miscellaneous fixed costs at Dfl. 5 000 per farm and at Dfl. 60 ha^{-1}.

13.6 Farm budgets

The computer calculated that for a farm with an area of 60 ha cultivated land the farmer himself would have to spend for field work 732, 781 and 886 h per year, with loose-soil husbandry, no-tillage and rational tillage, respectively. It is evident from Table 106 that a substantial proportion of the work on a 60 ha farm is carried out by a contractor. With own machinery the potential number of man-hours per ha was about 18, which was reduced to 12 – 15 hours by contract work. In the computer program, the possibility was included of the presence of a powerful tractor, which is capable to do all ploughing and harvesting root crops. However, in the present experiment such a tractor was sometimes not chosen, although the labour was available, because it was less expensive to engage a contractor. Plant protection products appeared to be an important item of the variable costs, especially in System B1. The fixed costs were similar for all systems.

Table 106. Summary of farm budget (Dfl. ha $^{-1}$) for a farm with an area of 60 ha cultivated land.

Budget components	Loose-soil husbandry (A)	No-tillage (B1)	Rational tillage (C)
Gross returns	5 397	4 949	5 418
Variable costs			
Seed	414	413	413
Fertilizer	464	465	419
Plant protection products	545	747	579
Rest	347	372	355
Total	1 770	1 997	1 766
Contractor's costs			
Ploughing and fixed-tine cultivation	155		122
Rotavation	81	120	38
Harvesting potatoes	235	235	235
Harvesting sugar beet	143	143	143
Transport of products	12	30	12
Rest		30	4
Total	626	558	554
Fixed costs			
Rent	954	954	954
Farm buildings	588	572	598
Machines and implements	541	564	566
Labour farmer	750	750	750
Miscellaneous	143	143	143
Total	2 976	2 983	3 011
Total costs	5 372	5 538	5 331
Profit	25	589	87
Difference with rational tillage	−62	−676	-
Difference in % of gross returns	-1.2	-13.7	-

13.7 Farm area and profit

Farm budgets have been made in the way described above for all farm sizes under consideration (36 – 96 ha). Figure 95 clearly illustrates that the calculated profit is considerably lower with no-tillage than with the two other soil tillage systems for all farm sizes. The profit on all farm sizes is with loose-soil husbandry about Dfl. 50 ha $^{-1}$ and with no-tillage about Dfl. 700 ha $^{-1}$ lower than with 'rational' tillage. Table 107 gives an analysis of the differences in profit relative to rational tillage for a farm of 60 ha. It shows that the mean difference in returns between loose-soil husbandry and rational tillage is small but negative and is accompanied but somewhat higher costs, mainly because the amount of contract work is larger. The important negative results of no-tillage are caused mainly by the smaller gross returns of potatoes and sugar beet and the higher cost of plant protection products.

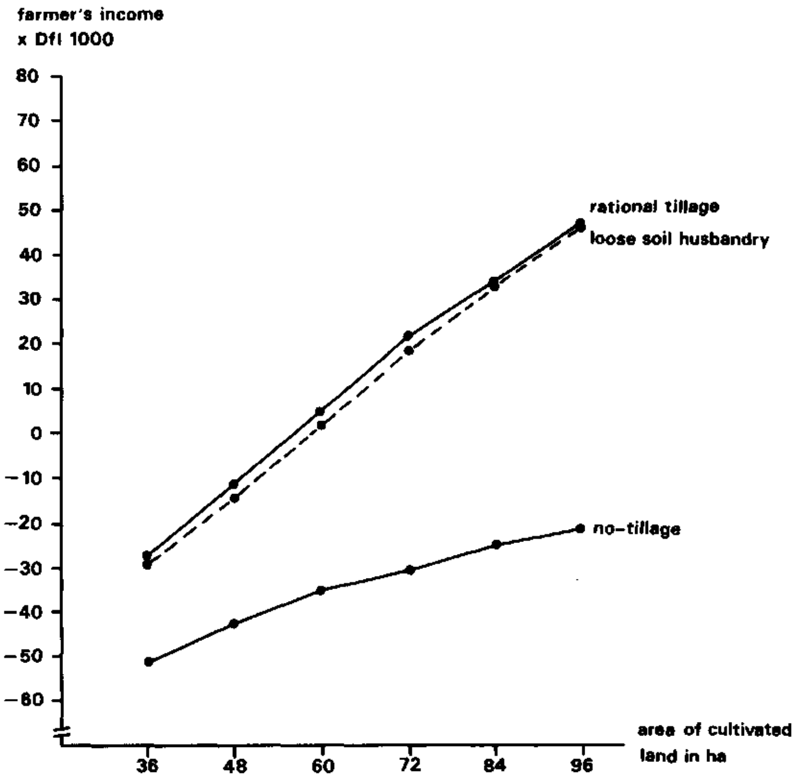


Fig. 95. Farm area and farmer's income.

Table 107. Profit components (Dfl. ha⁻¹) of loose-soil husbandry and no-tillage, relative to rational tillage.

Component	Loose-soil husbandry (A)			No-tillage (B1)		
	Pos.	Neg.	Total	Pos.	Neg.	Total
Returns						
Cereals	+26	-		+34	-	
Potatoes	-	-32		-	-295	
Sugar beet	-	-15		-	-208	
Total	+26	-47	-21	+34	-503	-469
Costs						
Fertilizer	-	-45		-	-46	
Plant protection products	+35	-		-	-168	
Other variable costs	+6	-		-	-17	
Contractor	-	-72		-	-4	
Fixed costs	+35	-		+28	-	
Total	+76	-117	-41	+28	-235	-207
Profit			-62			-676

13.8 Required gross returns

Tables 108 and 109 indicate how much the returns with loose-soil husbandry or no-tillage should increase to yield a profit equal to the profit with rational tillage. The required increase in returns has been expressed as a percentage of the gross returns of the system in question and in a percentage of the gross returns in rational tillage. No allowance was made for the difference in some costs resulting from higher returns. It can be concluded that the gross returns of loose-soil husbandry and no-tillage should rise by about 1% and 14%, respectively to achieve the same profit as with rational tillage at all farm sizes. This would make returns of no-tillage some 4% higher than those realized by rational tillage. This higher returns are needed to compensate for the higher variable costs.

Table 108. Gross returns of loose-soil husbandry required to achieve the same profit as for rational tillage, for different farm sizes.

Farm size (ha)	Difference in profit (Dfl. ha⁻¹)	Required gross returns		
		Dfl. ha⁻¹	Percentage	
			loose-soil husbandry (A)[a]	rational tillage (C)[b]
36	-53	5 450	101.0	100.6
48	-61	5 458	101.1	100.7
60	-62	5 459	101.1	100.8
72	61	5 458	101.1	100.7
84	-12	5 409	100.2	99.8
96	-15	5 412	100.3	99.9

a. Dfl. 5 397 per ha = 100% (cf. Table 106).
b. Dfl. 5 418 per ha = 100% (cf. Table 106).

Table 109. Gross returns of no-tillage required to achieve the same profit as for rational tillage, for different farm sizes.

Farm size (ha)	Difference in profit (Dfl. ha⁻¹)	Required gross returns		
		Dfl. ha⁻¹	Percentage	
			no-tillage (B1)[a]	rational tillage (C)[b]
36	659	5 608	113.3	103.5
48	-665	5 614	113.4	103.6
60	676	5 625	113.7	103.8
72	-709	5 658	114.3	104.4
84	-707	5 656	114.3	104.4
96	-716	5 665	114.5	104.6

a. Dfl. 4 949 per ha = 100% (cf. Table 106).
b. Dfl. 5 418 per ha = 100% (cf. Table 106).

13.9 Conclusions

1. The financial balance of the crop rotation, calculated for farm sizes from 36 – 96 ha, were similar for loose-soil husbandry and 'rational' tillage. However, for no-tillage the balance was about Dfl. 675 ha^{-1} lower.

2. Differences in financial results between no-tillage and rational tillage were caused mainly by the smaller gross returns of potatoes and sugar beet and by the higher cost of plant protection products.

3. Gross returns should rise by 14% in no-tillage to achieve the same financial results as in rational tillage.

4. To compensate for the higher variable costs in no-tillage the gross returns of no-tillage should be some 4% higher than the gross returns of rational tillage.

5. The gross returns of loose-soil husbandry should increase by only about 1% to achieve the same profit as with rational tillage.

Literature

Noordam W.P. & M. van der Ham, 1980. Kwantitatieve informatie 1980 – 1981 voor de akkerbouw en groenteteelt in de vollegrond. P.A.G.V. Lelystad, Publikatie nr. 10, 157 p.

14 After-effects

14.1 Introduction

C. van Ouwerkerk

After termination of the experiment, on 26 and 27 November 1979 the entire former experimental field Ws38 was ploughed lengthwise (East-West) to a depth of about 30 cm with a three-body reversible plough (working width 1.20 m). Due to much rain in November, the sugar beet harvest had had to be delayed until 20 November. At harvest the soil was still wet and, therefore, one had to wait for another full week until the soil had dried enough to be fit for ploughing.

During ploughing, drawbar pull was continuously recorded by means of a telemetry system and working depth was measured twice. Both measurements were carried out in the centre part (30 m long) of each former plot (total length 50 m). Directly after ploughing the degree of crumbling, soil surface roughness, covering of stubble and trash were visually estimated on all plots of Repetition I, while on plots with a previous crop of spring barley soil surface roughness and upheaval were determined by means of a reliefmeter (Kuipers & van Ouwerkerk, 1963). In spring these measurements were repeated and complemented with the visual estimation of the degree of superficial soil slaking.

On 20 March 1980, just before seedbed preparation for the potatoes, which were grown on the entire former experimental field, thermal and false-colour images were taken from an aircraft, soil samples of the 0 – 5 cm layer were collected for moisture content determinations, and terrestrial black-and-white photographs and slides were made.

Directly after seedbed preparation, on the former plots with previous crop spring barley of Repetition I, several characteristics of the seedbed, and pore space, moisture and air content in the 2 – 7 cm layer below the seedbed were determined. On 11 June 1980, on all plots moisture content was determined in the 0 – 10 cm depth (the loose soil of the potato ridge) and in the 10 – 20 and 20 – 30 cm depth (0 – 10 and 10 – 20 cm below the ridges). Soil structure of the loose soil in the ridges was visually estimated. On 19 June 1980, undisturbed core samples were taken for determination of pore space and moisture and air content in field moist condition and at pF 2.0 in the 12 – 17 and 22 – 27 cm layers of the former loose-soil husbandry and no-tillage plots of Repetition I.

14.2 Drawbar pull at ploughing

U.D. Perdok

From Table 110 it appears that, on average, ploughing depth did not differ much between systems. However, specific ploughing resistance was about 20% higher in Systems B1 and B2 than in Systems A and C. Between Systems B1 and B2 and between Systems A and C there were no significant differences. Especially in Systems A and C, there was a marked effect of previous crops: with spring barley specific ploughing resistance was about 18% higher than with potatoes. In System B1, this difference was only 7%. Apparently the large amount of loose soil left on the surface at potato harvest reduced specific ploughing resistance.

At ploughing no determinations of pore space, moisture and air content were made. However, pore space just before ploughing may be concluded from the core samplings carried out by Boone and van Ouwerkerk in September and October 1979 (before root crop harvest) and 15 November 1978 (after harvest of root crops). From Fig. 96 it appears there is a fair negative correlation between pore space and drawbar pull (r = −0.81). The untilled soil showed a much larger variability than the tilled soil.

Table 110. Specific ploughing resistance and ploughing depth (26 and 27 November 1979).

System	1979 crop	Specific resistance ($kN\ m^{-2}$)	Ploughing depth (m)	n
A	Potatoes	45.5	0.306	22
	Winter wheat	48.9	0.295	22
	Sugar beet	49.8	0.280	12
	Spring barley	54.5	0.275	12
	Mean	49.7[a]	0.289	
B1	Potatoes	57.9	0.286	12
	Winter wheat	55.4	0.302	12
	Sugar beet	62.3	0.269	6
	Spring barley	62.1	0.292	6
	Mean	59.4	0.287	
B2	Winter wheat	57.9	0.289	12
	Spring barley	65.6	0.286	4
	Seed grass	59.2	0.293	12
	Field beans	66.7	0.287	4
	Mean	62.4	0.289	
C	Potatoes	49.3	0.308	22
	Winter wheat	52.5	0.295	22
	Sugar beet	50.8	0.287	12
	Spring barley	56.1	0.273	12
	Mean	52.2	0.291	

a. L.S.D. = 4.47.

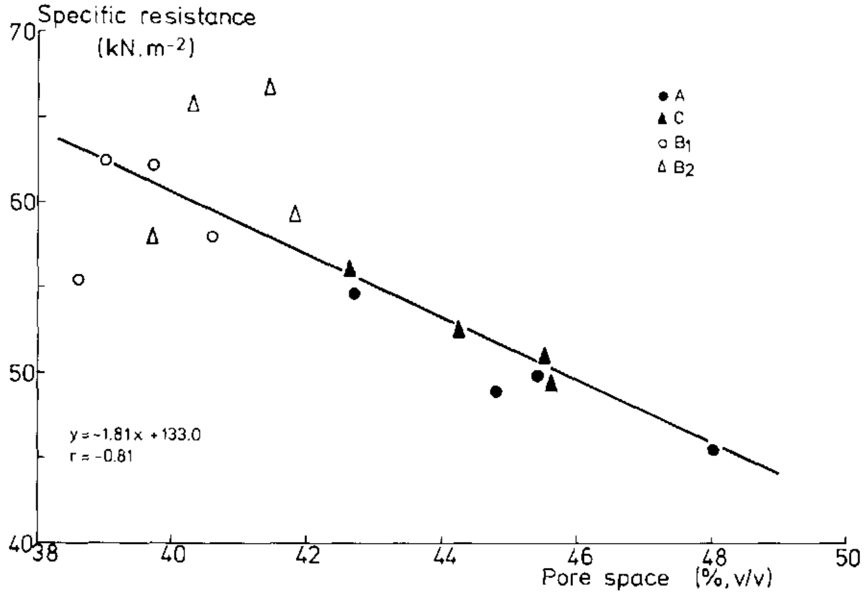


Fig. 96. Relationship between mean pore space in the 12 – 27 cm layer and mean specific ploughing resistance, 26 and 27 November 1979.

14.3 Effects of ploughing

C. van Ouwerkerk

At ploughing, after previous crops potatoes (System B2: seed grass), winter wheat and spring barley, the degree of soil crumbling was similar for all tillage systems (Table 111). However, after sugar beet (System B2: field beans), soil crumbling was much less in Systems A and C (4+) than in Systems B1 and B2 (7). In Systems A and C, soil crumbling was much less on plots with previous crop sugar beet (4+) than on plots with previous crops potatoes (6) and spring barley (6½). In all systems the previous crop winter wheat induced more soil crumbling (7½) than any other previous crop.

Soil surface roughness (Table 112) showed the reverse of soil crumbling which, in view of the strong correlation between both parameters (Fig. 97a), is not surprising. The covering of stubble and trash was very good on all plots (Table 113).

After ploughing on plots with previous crop spring barley the measured soil surface roughness (Table 114) in Systems B1 and B2 was only a little less than in Systems A and C. However, the upheaval in Systems B1 and B2 was about 40% larger than in Systems A and C, which correlates with the denser soil at ploughing in Systems B1 and B2 (Fig. 96).

Based on the upheaval measurements and the mean ploughing depths, the calculated pore space after ploughing (Table 115) was even larger in Systems B1 and B2 than in Systems A and C. Thus, by ploughing the originally much denser soil became somewhat looser than the orginally looser soil.

In spring (13 February 1980), soil surface roughness on all plots appeared to be

Table 111. Visual estimation of soil crumbling at ploughing on Repetition I, 30 November 1979[a].

1979 crop	A	C	B1	B2	Mean
Potatoes (B2: seed grass)	6	6	6½	7	6½
Winter wheat	7½	7	7½	8	7½
Sugar beet (B2: field beans)	4	4½	7	7	5½
Spring barley	6½	6½	6½	7	6½
Mean	6	6	7	7+	6½

a. 1 = not crumbled; 10 = intensively crumbled.

Table 112. Visual estimation of soil surface roughness after ploughing on Repetition I, 30 November 1979[a].

1979 crop	A	C	B1	B2	Mean
Potatoes (B2: seed grass)	9	9	8½	8	8½
Winter wheat	7½	8	7½	7	7½
Sugar beet (B2: field beans)	9½	9½	8	8	9−
Spring barley	8	8½	8½	8	8+
Mean	8½	9−	8+	8−	8+

a. 1 = very smooth; 10 = very rough.

Table 113. Visual estimation of the covering of stubble and trash after ploughing on Repetition I, 30 November 1979[a].

1979 crop	A	C	B1	B2	Mean
Potatoes (B2: seed grass)	9	9	9	9	9
Winter wheat	9	9	9	9	9
Sugar beet (B2: field beans)	8	8	9	9	8½
Spring barley	9	9	9	9	9
Mean	9−	9−	9	9	9−

a. 1 = not covered; 10 = fully covered.

Table 114. Soil surface roughness and upheaval on plots of Repetition I with previous crop spring barley.

Date	Roughness (100 log S_x)[a]				Upheaval (cm)			
	A	C	B1	B2	A	C	B1	B2
30/11/79	69	66	60	57	7.1	9.2	11.2	11.9
13/02/80[b]	–	48	48	44	–	4.3	6.5	7.5
Difference	–	18	12	13	–	4.9	4.7	4.4

a. S_x *in cm.*

b. In spring the measurement in System A failed.

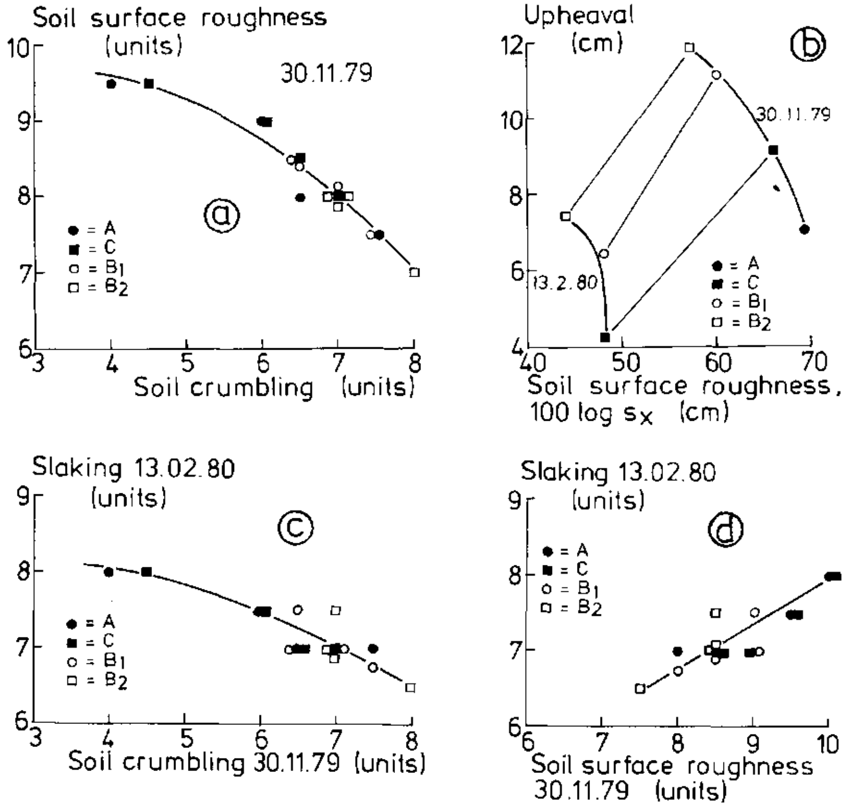


Fig. 97a. Relationship between visually estimated soil crumbling at ploughing and soil surface roughness directly after ploughing, 30 November 1979.

Fig. 97b. Relationship between measured soil surface roughness and upheaval, directly after ploughing (30 November 1979) and in early spring (13 February 1980).

Fig. 97c. Relationship between visually estimated soil crumbling at ploughing (30 November 1979) and superficial slaking in early spring (13 February 1980).

Fig. 97d. Relationship between visually estimated soil surface roughness directly after ploughing (30 November 1979) and superficial slaking in early spring (13 February 1980).

Table 115. Calculated mean pore space in the 12 - 17 cm depth of the ploughed layer of Repetition I.

Date	A	C	B1	B2
25/11/79 (before ploughing)	42.7	42.6	39.7	40.3
28/11/79 (after ploughing)	54.5	57.1	56.4	58.4
13/02/80 (in spring)		50.4	50.7	53.1

decreased to about 75% of the value found in autumn (Table 114). Relatively and absolutely, the largest decrease in upheaval was found in System C (53%, 4.9 cm). In Systems B1 and B2 the decrease in upheaval was 4.5 cm, i.e. about 40% of the value found in autumn. Consequently, in spring the upheaval on the much stronger crumbled soil in Systems B1 and B2 was about 60% larger than in System C. The calculated mean pore space was now about the same for Systems B1 and C and still clearly larger in System B2 (Table 115).

The relationship between soil surface roughness and upheaval is shown in Fig. 97. It appears that, generally, this relationship is positive (difference autumn - spring). However, caused by the difference in soil crumbling, both in autumn and in spring, a larger soil surface roughness was attended by a smaller upheaval.

On 13 February 1980 again soil surface roughness was visually estimated (Table 116) as was superficial soil slaking (Table 117). Differences in roughness among previous crops and tillage systems were now smaller than directly after ploughing (Table 112), but soil surface roughness was still largest and soil slaking least after the previous crop sugar beet in Systems A and C. However, in view of the high level of the estimated soil slaking figures, it is clear that superficial slaking did hardly occur. Nevertheless, there was a clear correlation between superficial soil slaking, soil crumbling and roughness produced by ploughing (Figs. 97c and 97d).

Table 116. Visual estimation of soil surface roughness on Repetition I in early spring[a], 13 February 1980.

1979 crop	A	C	B1	B2	Mean
Potatoes (B2: seed grass)	7½	7½	7½	8	7½
Winter wheat	7½	7	7	7	7
Sugar beet (B2: field beans)	8½	8½	7½	7	8–
Spring barley	7½	7	7	7	7
Mean	8–	7½	7+	7+	7½

a. 1 = very smooth; 10 = very rough.

Table 117. Visual estimation of superficial soil slaking on Repetition I in early spring[a], 13 February 1980.

1979 crop	A	C	B1	B2	Mean
Potatoes (B2: seed grass)	7½	7½	7½	7½	7½
Winter wheat	7	7	7–	6½	7–
Sugar beet (B2: field beans)	8	8	7	7	7½
Spring barley	7	7	7	7	7
Mean	7½	7½	7	7	7+

a. 1 = severely slaked; 10 = not slaked.

14.4 Emittance and reflectance characteristics

J.G. Lamers & C. van Ouwerkerk

On 20 March 1980, a cold but sunny day (maximum temperature 4.8° C), thermal and false-colour images were taken at 14.00 h from an aircraft of the National Aerospace Laboratory (NLR). Subsequently, the false-colour images were transformed into false-colour slides. Detailed information on the methods used is given in Chapter 12. On the right-hand side of the experimental field, where in the autumn of 1979 ploughing resistance had been measured, reflectance was generally higher and colour density of the false-colour slides was lower than on the left-hand side, where the ploughing had been performed with a different plough setting. To correct for this difference, blue and red densities of the false-colour slides of the right-hand side were multiplied by 1.28 and 1.23, respectively. In this way the reflectance of the former tillage plots on both parts of the field could be compared.

Because the resolution of the false-colour slides and the thermal images was too low, possible differences between former Systems B1 and B2 could not be detected. Therefore, in the following, Systems B1 and B2 are taken together and named System B.

Temperature differences between tillage systems were significant ($P<0.001$). System B had the highest surface temperatures and System A the lowest (Table 118). After potatoes, the soil appeared to have higher surface temperatures than after other crops.

Reflectance measurements on the false-colour slides showed a high red density for Systems A and C after sugar beet, and for System B after potatoes (Table 119). Just as on

Table 118. Surface temperature deviation (°C) from the overall mean value for bare, ploughed soil, 20 March 1980.

1979 crop	A	C	B[a]	Mean
Potatoes	0.10	0.33	0.55	0.26
Winter wheat	0.37	-0.07	0.16	-0.09
Sugar beet	-0.44	-0.25	0.28	-0.14
Spring barley	0.38	-0.22	0.50	0.03
Mean	0.32	-0.05	0.37	0

a. Average of Systems B1 and B2.

Table 119. Red density of the false-colour slides[a], 20 March 1980.

1979 crop	A	C	B[b]	Mean
Potatoes	1.76	1.79	1.91	1.82
Winter wheat	1.74	1.74	1.79	1.76
Sugar beet	1.86	1.89	1.75	1.83
Spring barley	1.83	1.80	1.70	1.78
Mean	1.80	1.80	1.79	1.80

a. 0 = white; 3 = black.
b. Average of Systems B1 and B2.

19 June 1979, dark and light features across the experimental field could be seen (Fig. 98), which were related to the former drainage system (Chapter 12).

Differences in soil moisture content of the 0 - 5 cm layer were small (Table 120). Nevertheless, System B had a significantly lower soil moisture content than System A ($P<0.01$). There was rather good correlation ($r = -0.81$) between soil moisture content in the 0 - 5 cm layer and soil surface temperature (Fig. 99). According to a step-by-step multiple linear regression analysis, other parameters, such as soil surface roughness on 30 November 1979 and 13 February 1980 (Table 114), degree of superficial soil slaking on 13 February 1980 (Table 117), the degree of soil crumbling and covering of stubble and trash on 30 November 1979 (Tables 111 and 113), did not contribute significantly to the rest variance in the soil surface temperature - soil moisture relationship.

The red density of the false-colour images correlated well ($r = 0.72$) with the estimated soil surface roughness on 13 February 1980 (Fig. 100). Because soil surface roughness

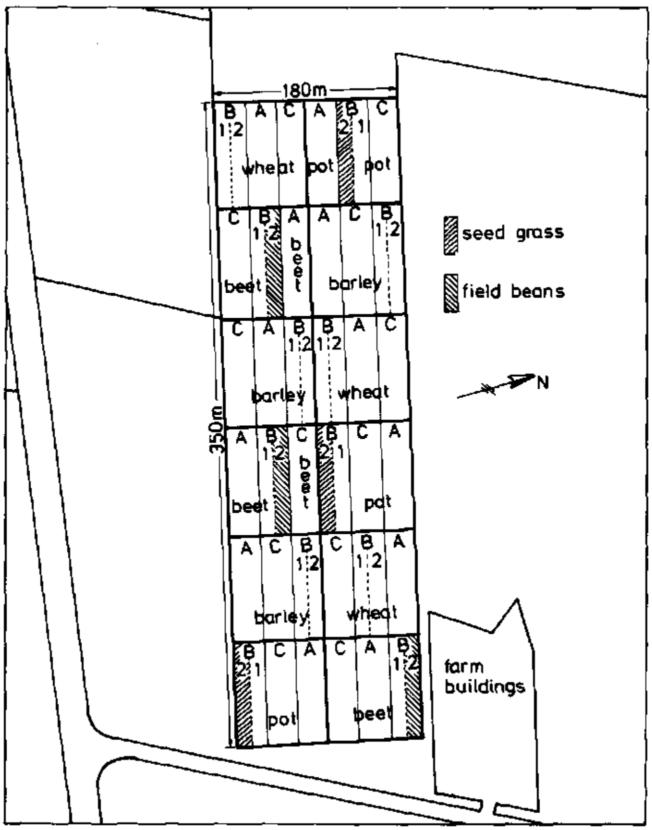


Fig. 98. Left: oblique thermal image of the former experimental field on 20 March 1980, showing dark features for low temperatures (temperature range on the image is about 5° C). Right: plan of the experimental field with crops grown in 1979 (A=loose-soil husbandry; C=rational tillage; B1=no-tillage with root crops; B2= no-tillage without root crops).

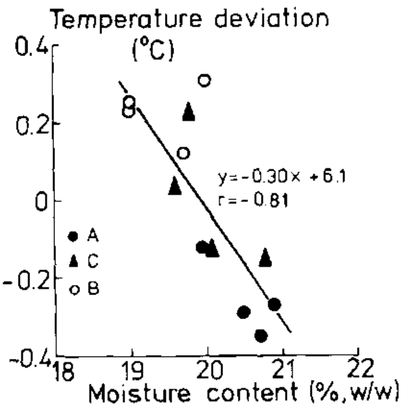


Fig. 99. Relationship between moisture content of the 0 - 5 cm layer and soil surface temperature deviation from the overall mean value, 20 March 1980.

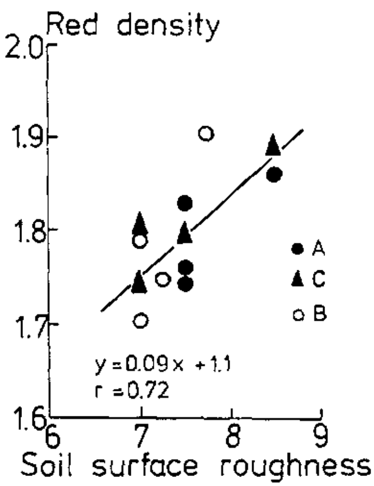
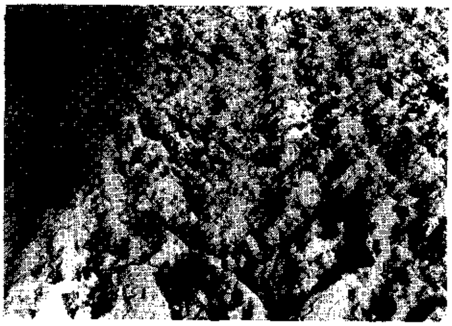


Fig. 100. Relationship between soil surface roughness on 13 February 1980 and red density of the false-colour slide, 20 March 1980.

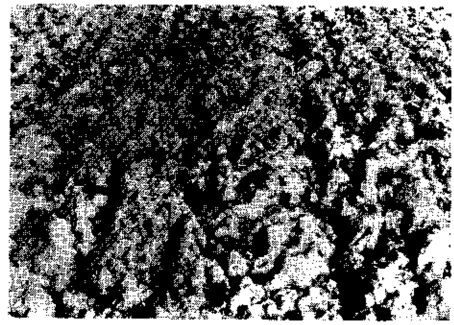
Table 120. Moisture content (%, w/w) of the 0 5 cm layer, 20 March, 1980.

1979 crop	A	C	B[a]	Mean
Potatoes	20.0	19.8	19.0	19.6
Winter wheat	20.9	19.6	19.7	20.1
Sugar beet	20.7	20.8	19.0	20.2
Spring barley	20.5	20.0	20.0	20.2
Mean	20.5	20.1	19.4	20.0

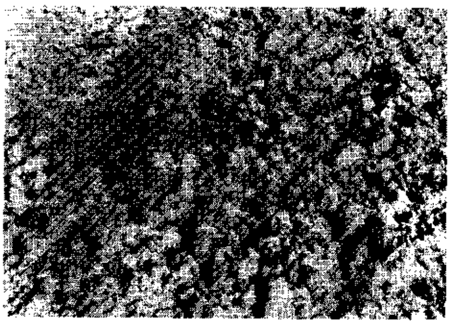
a. Average of Systems B1 and B2.



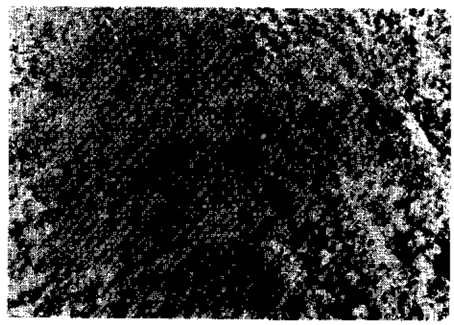
System A



System C



System B1



System B2

Fig. 101. View of the plots of Repetition I with previous crop sugar beet (field beans in System B2), 20 March 1980.

and soil slaking are related (Fig. 97), there was a reasonable correlation between red density and the estimated degree of superficial soil slaking ($r = 0.63$). The small differences in soil surface roughness and degree of slaking are illustrated in Fig. 101. A step-by-step multiple linear regression analysis showed that besides soil surface roughness no other measured parameter could explain the rest variance in the red density - soil surface roughness relationship.

14.5 Seedbed characteristics and soil structure

C. van Ouwerkerk & F.R. Boone

On 15 April 1980 the seedbed for potatoes was prepared with a powered rotary harrow. In Systems B1 and B2, where soil crumbling at ploughing was much stronger, the loose layer was clearly thicker, it contained less clods and was, on average, much finer (cf. mean aggregate diameter) than in Systems A and C (Table 121). Also soil surface roughness, bulk density and moisture content of the loose layer were less.

At 2 - 7 cm depth below the seedbed mean pore space and moisture content were higher in Systems B1 and B2 than in Systems A and C (Table 122). The smaller standard

Table 121. Characteristics of the seedbed for potatoes on the plots with previous crop spring barley of Repetition I, 15 April 1980.

Characteristics	A	C	B1	B2
Roughness of surface (s_x, mm)[a]	11.2	12.3	8.0	10.1
Roughness of subsoil (s_x, mm)[a]	5.6	4.3	4.4	5.2
Depth of the loose layer ($\bar{d}$, cm)	6.1	6.2	7.4	8.2
Variation in depth (s_d, cm)	1.8	1.5	1.2	1.4
Aggregates > 20 mm (%, w/w)	9.8	7.5	2.5	2.6
Aggregates < 2.5 mm (%, w/w)	41.4	40.3	39.5	46.8
Mean aggregate diameter (mm)	7.1	6.6	4.8	4.3
Moisture content (%, w/w)	11.7	12.5	10.2	10.9
Dry bulk density (kg m^{-3})	950	960	880	880

a. x = vertical distance (mm) between the soil surface or the surface of the subsoil and an arbitrary horizontal line.

Table 122. Pore space, moisture content and air content in the 2 – 7 cm depth below the seedbed for potatoes on the plots with previous crop spring barley of Repetition I, 15 April, 1980.

Statistic	System	Pore space (%, v/v)	Moisture content (%, w/w)		Air content (%, v/v)	
			field	pF 2.0	field	pF 2.0
$\bar{x}$	A	48.4	21.0	23.7	19.5	15.8
	C	46.9	21.4	23.4	16.6	13.8
	B1	50.6	22.1	23.8	21.6	19.2
	B2	49.8	23.3	24.5	18.6	17.0
s_x	A	3.2	1.4	1.1	5.0	4.7
	C	3.1	1.0	0.8	3.8	4.0
	B1	2.0	1.6	0.8	3.2	3.4
	B2	2.0	1.6	1.6	4.2	4.1

deviation of mean pore space found in Systems B1 and B2 indicates a more homogeneous soil, which may be explained by the stronger soil crumbling at ploughing.

On 11 June 1980, after 6 weeks drought (Fig. 17), the ridges (0 – 10 cm) were much drier than the layers below the ridges (on average 14.0, 20.7 and 21.6% (w/w)), respectively; (Table 123). Generally, the differences between former tillage systems were only small. The exception is System B2 where moisture content at 20 – 30 cm depth was always about 2% (w/w) higher than in the other systems. This phenomenon may be ascribed to the turning under of a toplayer which was much higher in organic matter than in the other systems.

According to the results of the visual estimation (Table 124) in all sytems soil structure in the potato ridges was very good (8) and independent of the previous crop. Below the ridges (10 – 20 cm depth) in plots which previous crops potatoes, seed grass (System B2), sugar beet and spring barley, soil structure was marked 6; however, with previous crops field beans (System B2) and winter wheat the mark was 7, which is probably related to

Table 123. Moisture content (%, w/w) in potato ridges (0 - 10 cm depth) and below potato ridges (10 - 20 and 20 - 30 cm depth) on the plots of Repetition I, 11 June 1980.

1979 crop	Depth (cm)	A	C	B1	B2
Potatoes (B2: seed grass)	0 - 10	14.7	14.8	14.1	14.8
	10 - 20	21.2	20.3	21.6	22.0
	20 - 30	22.1	21.4	21.5	23.8
Winter wheat	0 - 10	14.0	13.4	13.8	13.2
	10 - 20	20.2	20.9	21.3	20.5
	20 - 30	20.8	20.1	22.3	23.0
Sugar beet (B2: field beans)	0 - 10	12.6	12.8	13.7	15.4
	10 - 20	20.5	19.3	19.1	20.5
	20 - 30	22.0	21.3	20.6	23.5
Spring barley	0 - 10	14.1	13.8	13.8	15.2
	10 - 20	19.6	20.2	21.1	23.2
	20 - 30	20.2	19.9	20.1	22.2

Table 124. Visual estimation of soil structure in potato ridges (0 - 10 cm depth) and below potato ridges (10 - 20 cm depth) on the plots of Repetition I, 11 June 1980.

1979 crop	Depth (cm)	A	C	B1	B2
Potatoes (B2: seed grass)	0 - 10	8	8	8	8–
	10 - 20	6	6+	6	6
Winter wheat	0 - 10	8	8	8	8
	10 - 20	6+	7	7+	7+
Sugar beet (B2: field beans)	0 - 10	8	8	8	8
	10 - 20	6	6	6	7
Spring barley	0 - 10	8	8	8	8
	10 - 20	6–	6+	6+	6½

Table 125. Average pore space, moisture and air content below potato ridges on Repetition I, 19 June 1980.

Depth below the ridge (cm)	System	Pore space (%, v/v)	Moisture content (%, w/w)		Air content (%, v/v)	
			field	pF 2.0	field	pF 2.0
2 - 7	A	47.6	17.8	23.7	22.6	14.6
	B1	46.8	17.7	22.9	21.5	14.4
	B2	47.4	17.6	23.0	22.7	15.1
12 - 17	A	47.4	19.1	23.7	20.5	14.1
	B1	47.3	19.5	23.4	20.0	14.5
	B2	47.8	19.8	23.8	20.3	14.7

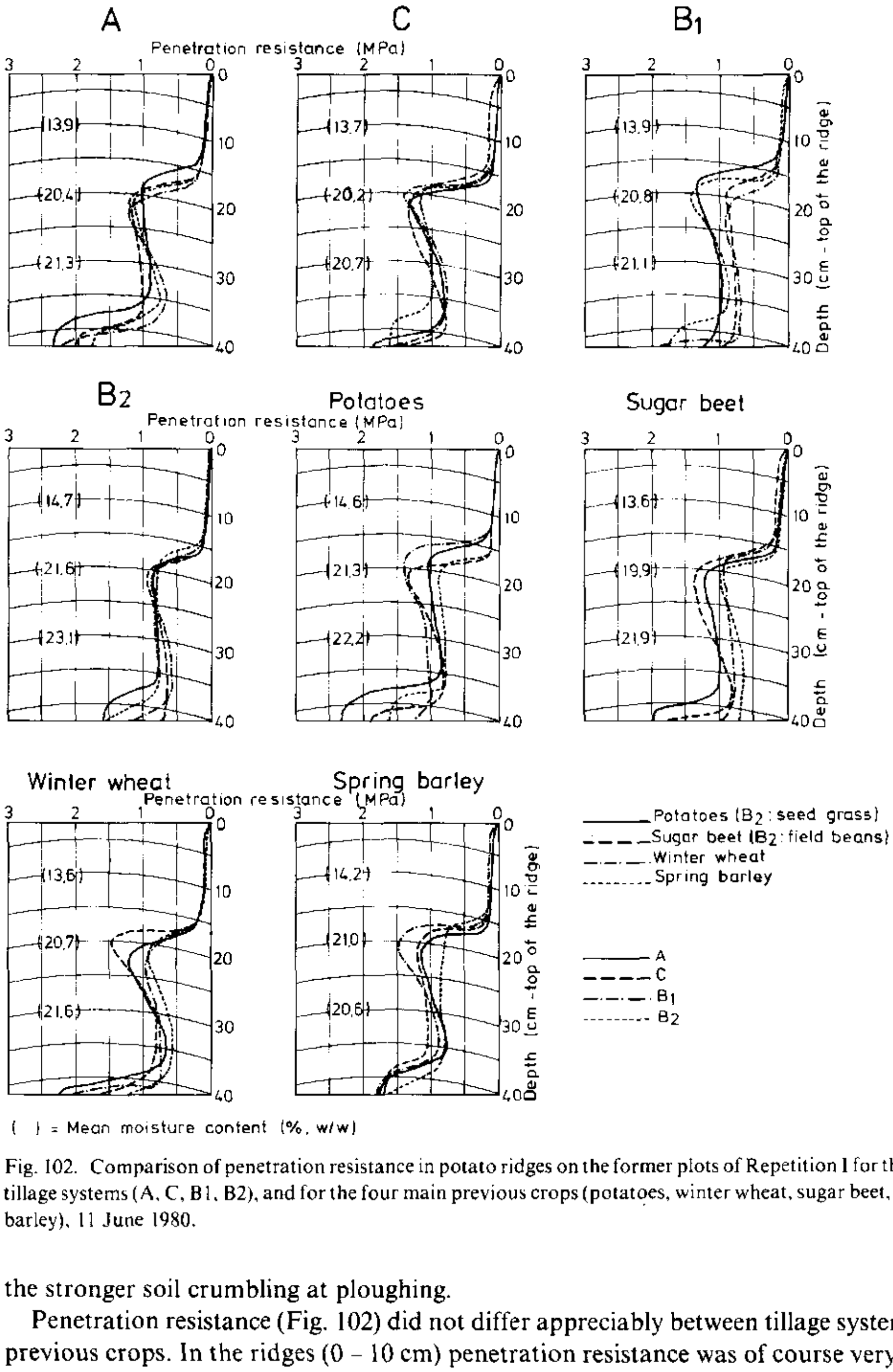


Fig. 102. Comparison of penetration resistance in potato ridges on the former plots of Repetition I for the four tillage systems (A, C, B1, B2), and for the four main previous crops (potatoes, winter wheat, sugar beet, spring barley), 11 June 1980.

the stronger soil crumbling at ploughing.

Penetration resistance (Fig. 102) did not differ appreciably between tillage systems or previous crops. In the ridges (0 – 10 cm) penetration resistance was of course very low, but below the ridges, too, penetration resistance was only moderate (about 1 MPa), which is related to the generally good soil structure found here (cf. Table 124).

On 19 June 1980, after some 20 mm of rain, differences in moisture content below the ridges had disappeared (Table 125) and also pore space and air content were similar for all systems. Thus, it may be concluded that, even although performed under wet soil conditions, ploughing to about 28 cm depth fully removed the effect of eight years of no-tillage on soil structure.

14.6 Weed development and potato growth

W.A.P. Bakermans & C. Vader

Generally, in the period 1976 – 1979, weeds were effectively controlled and, with some additional sprayings and some extra hand-weeding, weed coverage could be kept below the critical level. On 10 October 1979, at the termination of the experiment, all plots on which in 1979 winter wheat, spring barley, seed grass or field beans had been grown and the grassed strips separating experimental blocks, were treated with glyphosate (2.16 kg ha^{-1} a.i.) to control all perennial weeds.

In 1980, the potato crop was successfully sprayed with 1 kg ha^{-1} of sencor and, therefore, in 1980 hardly any annual weeds occurred. The 1979 glyphosate treatment proved to be very effective, except for the former field beans plots, where the glyphosate was applied too soon after harvest when the weeds were still too small. On these plots some large patches with mainly *Cirsium arvense* occurred (Table 126).

Due to the effective control with glyphosate, the after-effects of the different tillage systems on weed development were generally small. On the former potato and sugar beet plots, which were not treated with glyphosate, in 1980 more or less large patches of mainly *Cirsium arvense, Tussilago farfara, Polygonum amphybium, Elytrigia repens* and *Equiseteum arvense* occurred, especially in System B1. In addition, on all former potato plots many volunteer potatoes occurred: between two new potato ridges on average 2 – 3 plants per m were counted.

Foliage development of the potato crop was most abundant on the former seed grass plots and it decreased in the order grassed strips, potatoes, field beans, winter wheat, spring barley. Foliage development was distinctly least on the former sugar beet plots.

Table 126. Estimated values for weed coverage on 9 June 1980[a].

Previous crop	Tillage system			
	A	B1	B2	C
Potatoes	4[b]	5[b]	–	3[b]
Seed grass	–	–	10	–
Sugar beet	7	5	–	8
Field beans	–	–	7	–
Spring barley	9	9	9	9
Winter wheat	9	9	9	9

a. 10 = no weeds; 5 = rather many weeds: the crop has to be hoed; 1 = very many weeds.

b. Many volunteer potatoes.

Dying of the foliage showed the same order, i.e. the potatoes on the former seed grass plots remained green longest. Although no yields were determined, the impression was gained that the potato yields on plots that remained green for a longer time were higher than on plots where the plants died earlier. It is likely that these phenomena are related to the different amounts of nitrogen left in the soil by the previous crops.

Compared with the effect of the previous crop, the after-effect of the former tillage systems was only small. Only on the former winter wheat and spring barley plots foliage developed slightly better and died slightly later in System B2 than in Systems A, B1 and C. Probably this is caused by a greater nitrogen supply by nitrification on former B2 plots, due to tillage for the first time after 8 years of no-tillage.

14.7 Conclusions

C. van Ouwerkerk, F.R. Boone, W.A.P. Bakermans, J.G. Lamers & U.D. Perdok

1. After termination of the experiment, at ploughing the entire former experimental field to 30 cm depth, specific ploughing resistance was about 20% higher, soil crumbling was much stronger and the upheaval brought about by ploughing was about 40% larger in Systems B1 and B2 than in Systems A and C.

2. During winter the more strongly crumbled soil of Systems B1 and B2 superficially slaked even less than in Systems A and C.

3. From thermal images it appeared that just before seedbed preparation, bare soil in System B had a 0.7°C higher surface temperature than System A. Surface temperatures correlated rather well ($r = -0.75$) with moisture content of the topsoil. Red density of false-colour slides was rather high after sugar beet in Systems A and C and after potatoes in System B. Red density correlated rather well ($r = 0.72$) with estimated soil surface roughness and reasonably ($r = 0.63$) with the estimated degree of superficial soil slaking.

4. The seedbed for potatoes in former Systems B1 and B2 was much thicker, it contained far less clods and was, on average, much finer than in Systems A and C. Directly below the seedbed mean pore space and moisture content were, respectively, 2.5% (v/v) and 1.5% (w/w) higher in Systems B1 and B2 than in Systems A and C.

5. In all former tillage systems soil structure in the potato ridges was very good. At 10 - 20 cm below the ridges moisture content in former System B2 was about 2% (w/w) higher than in the other systems, which was due to the turning under of a toplayer containing much more organic matter.

6. As judged by pore space in the subsequent potato growing season, even by ploughing under wet soil conditions the effect of 8 years no-tillage was fully removed.

7. Due to the effective control with glyphosate, which was applied in autumn 1979 on former winter wheat, spring barley, seed grass and field beans plots, the after-effects of the different tillage systems on weed development were generally small. On the former potato and sugar beet plots, which were not treated with glyphosate, in 1980 more or less large patches of perennial weeds occurred, especially in System B1.

8. The after-effect of the former tillage systems on potato development was only small. However, in System B2, on the former winter wheat and spring barley plots, better foliage development and later dying of the crop pointed to a greater nitrogen supply, due to tillage for the first time after 8 years of no-tillage.

15 General discussion

C. van Ouwerkerk, F.R. Boone, L.M. Lumkes & W.A.P. Bakermans

The experiment reported here has been carried on for 8 years, which means that the effects of a wide variety of weather conditions on the result of primary and secondary tillage and on crop development are included.

Since after the first crop rotation (1972 - 1975) the differences in soil structure between Systems A and C were smaller than hoped for, during the second crop rotation, the differences in primary tillage depth were increased by fixing ploughing depth in System A at 25 cm for all crops, and by reducing the depth of ploughing for potatoes and the depth of fixed-tine cultivation for cereals from 20 tot 15 cm in System C.

In System C, the decreased ploughing depth for potatoes brought the advantage that a 7-body skim plough with a working width of 1.75 m could be used, but the disadvantage that green manure grass could not be properly turned under so that it had to be killed off with paraquat. Fixed-tine cultivation to only 15 cm depth for winter wheat after potatoes had the consequence that less coarse clods from beneath could be mixed through the finely crumbled, loose soil left after potato harvest and, hence, resistance to soil slaking during winter was reduced.

In System B1, during the second crop rotation, preparation of a shallow seedbed for all crops improved seedling emergence as compared with the first crop rotation, during which only for potatoes a seedbed was prepared. It brought the added advantage that now all crops could be sown with the same equipment as in Systems A and C. The emergence of sugar beet was further safeguarded by removing the straw of the preceding winter wheat crop. Thus, during the second crop rotation, System B1 was a system of extremely reduced tillage and System B2 remained a very 'pure' kind of no-tillage.

At primary tillage, in System A, where a two-body plough with a working width of only 0.75 m was used, traffic intensity was larger than in System C, where in two out of four years a 3 m wide fixed-tine cultivator was used, a ploughing for potatoes a 1.75 m wide skim plough was applied, and only for sugar beet ploughing was performed as in System A. Moreover, during the second crop rotation, fixed-tine cultivation for spring barley was performed across the field.

In System A, in spring, the combination of seedbed preparation and sowing or planting required a large tractor on twin wheels with a track gauge of only 1.50 m (cf. Chapter 2). Thus, a considerable area was trafficked and the effect on soil structure of the increased difference in working depth and intensity of primary tillage between Systems A and C was smaller than intended.

Due to better weather and soil conditions at the time subsequent parts of the tillage systems were applied, soil structure in loose-soil husbandry and rational tillage was clearly better during the period 1976 - 1979 than during the period 1972 - 1975.

The excessively wet autumn and early winter of 1974 had a catastrophic effect on soil structure. However, owing to favourable weather conditions during the 1975 growing season, soil structure regenerated and, in Systems A and C, was considerably improved in the autumn of 1976, when primary tillage could be carried out under dry soil conditions. In Systems B1 and B2, however, in the 22 - 27 cm layer and, in the 12 - 17 cm layer especially, pore space and air content at pF 2.0 remained at a very low level. Therefore, in these layers, the differences in pore space between tilled and non-tilled soil were clearly larger in the second than in the first crop rotation. In the 12 - 17 cm layer of Systems B1 and B2, pore space nearly equalled the very low pore space of 39% (v/v) which, according to laboratory research (van Ouwerkerk, 1976), is the lowest possible pore space to be expected on this soil. The depth of this zone of maximum compaction accords with the findings of Söhne (1957) that maximum compaction is to be found at a depth of 0.5 - 0.7 times the tyre width (here 0.30 m). In System B1, because of root crop harvest and the accompanying heavy transport, soil density in this layer was slightly larger than in System B2. In the 2 - 7 cm layer, in both Systems B1 and B2, pore space was clearly higher than in deeper layers, due to seedbed preparation (System B1) and organic matter accumulation (especially System B2). However, this was attended by a higher moisture content at pF 2.0 and, therefore, in this layer air content at pF 2.0 was still low.

The non-tilled soil in System B2 favoured the earthworm population which produced about 85 biopores > 1.5 mm per m^2, as compared with only about 10 biopores > 1.5 mm per m^2 in Systems A and B1. The number of biopores < 1.5 mm was about five times as high in System B2 (475 per m^2) than in Systems A and B1 (85 per m^2).

On average, in tilled soil, at a soil water potential of - 10 kPa (pF 2.0), air content was about twice, and the gas diffusion coefficient about 4 times as high as in untilled soil. However, at small air contents (< 10%, v/v) the gas diffusion coefficient was slightly higher on untilled than on tilled soil. This indicates that pore continuity of the big(ger) pores was better on untilled than on tilled soil. In untilled soil, problems with the macro gas transport may be expected only under wet soil conditions (about pF 1.5), combined with a rather high oxygen consumption. This topic was further elucidated in Chapters 8 and 9.

Penetration resistance of untilled soil (about 2.5 MPa at pF 2.0) was 2 - 3 times as large as on tilled soil because of the clearly lower pore space, but also because of the lower moisture content at pF 2.0. The ploughpan was very compact in all systems, with a penetration resistance of about 2.0 MPa or more, a pore space of about 40% (v/v) and an air content at pF 2.0 of about 5% (v/v). In Systems A and C the structural boundary between the loose soil of the tilled layer and the compacted soil of the ploughpan, therefore, was abrupt. In System B1 a more gradual transition between loose and firm soil was found at a depth of 5 - 10 cm. In all systems the subsoil, with a penetration resistance of about 2.0 MPa, a pore space of about 45% (v/v) and an air content at pF 2.0 of < 10% (v/v), was not very favourable for root development.

Effective rooting depth, i.e. the lower boundary of the zone that contained 90% of the total number of roots visible on the wall of a profile pit, was in late summer in Systems A and C for winter wheat about 90 cm, for spring barley 80 cm, for sugar beet 50 cm and for potatoes only 30 cm, because potato roots were hardly capable of penetrating the ploughpan. In System B1, effective rooting depth was only slightly (5 - 10 cm) shallower than in Systems A and C. The number of roots did not vary much between Systems A and C but, on average, significantly fewer roots were formed in System B1. Thus, the looser structure of tilled soil clearly promoted root growth.

During the second crop rotation, in Systems A, B1 and C (which did not differ much), on average, in January, in the soil profile (0 - 100 cm depth), 75 kg ha^{-1} of N_{min} was found. However, due to differences in precipitation during autumn and winter, there were large differences between years.

In System B2, during the first four years of the experiment, N_{min} was much less than in the other systems and even in 1976 it was only 81%. However, in 1978, N_{min} was similar, and in 1979 it was even 37% higher. In System B1, already in the course of the first four years, N_{min} had increased from 60% to 100% of N_{min} in Systems A and C.

There was a marked effect of the previous crop on the amount of N_{min} in January. After winter wheat and spring barley, similar, small amounts were found, after sugar beet slightly higher amounts, and after potatoes the amount of N_{min} was about twice as high. After potatoes, probably due to superficial rooting, about 50% of N_{min} was located in the 60 - 100 cm layer, but after cereals and sugar beet only about 35% of N_{min} was found in this layer. In the first year of the second crop rotation (1976), significant effects of perennial nitrogen levels on the amount of N_{min} in the soil profile(0 - 100 cm) were not found.

The two kinds of nitrogen levels, 'annual' and 'perennial' did not fully come up to expectations. The annual nitrogen levels were each year the same but, in contrast to the perennial nitrogen levels, they were not replicated. Therefore, especially when data was missing, it was difficult to draw credible full-range nitrogen response curves. The amounts of fresh nitrogen fertilizer at perennial nitrogen levels P –, P and P + varied very much between years because they were adjusted to the total amount of mineral nitrogen found in the soil profile in January. Since 1977, for several crops, they differed even between the three replications of the experimental field. Consequently, replications were no longer true replications and statistical analysis became questionable.

The annual nitrogen response curves showed extreme differences between years and, therefore, it is not surprising that crop response to perennial nitrogen levels varied still more, depending on their position with respect to the annual nitrogen levels and the level and shape of the nitrogen response curve for the particular year. During the second crop rotation, however, as demonstrated by the annual nitrogen response curves, perennial nitrogen levels usually were sub-optimal and, therefore, there was nearly always a positive trend in yield with increasing fertilizer nitrogen. At comparable fresh nitrogen applications, yield results of perennial and annual nitrogen levels differed only slightly and not systematically. Thus, perennial nitrogen levels did not have demonstrable cumulative effects.

With potatoes in System A, when ridges were too small (1978), crop development was slower and yield was lower than in System C. However, when ridges had the proper quality, crop yield was equal to or higher and the grading coarser than in System C. In System B1, gross yield was reasonable if the crop was planted at the same date as in Systems A and C. However, the percentage of cullings was always higher and, thus, saleable yield was, on average, some 10 - 15% lower than in Systems A and C.

With winter wheat in System A, combining primary tillage and sowing in one pass usually produced a too-coarse seedbed, which reduced emergence when dry weather followed (autumn 1976). However, this could be compensated for by increasing the seed rate by 10 - 15%. In System C the seedbed generally was much finer than in System A, but usually it did not slake severely. In System B1 the seedbed was always too fine and, therefore, slaking could be so severe that the crop had to be resown with spring wheat (1976) or should have been additionally sown with spring wheat (1979). In System B2, due to problems with the sowing technique, it was necessary to increase the seed rate of cereals by 25%, to resow the winter wheat crop (1976) or to sow it additionally with spring wheat (1978). Yield levels in Systems A and C usually were about the same, but often at the highest annual nitrogen level System A yielded higher than System C. Provided plant density was high enough, System B1 yielded about the same as Systems A and C, but System B2 yielded nearly the same only at the highest annual nitrogen level.

Seedbed preparation and sowing of sugar beet in one pass (System A) proved to be not advisable because the soil often was too wet to obtain a suitable seedbed, and sometimes seed coulters clogged to the effect that the stand of the crop was very irregular and yields were reduced. Seedbed preparation only (System B1) was shown to be risky because it was difficult to realize a good seedbed in time. Moreover, the uneven surface, with many dips and ruts, resulted in an uneven working depth of the rotary harrow and, consequently, sowing depth in the very shallow seedbed was irregular. Unimpeded capillary rise was an advantage in dry periods (1976), but the large mechanical resistance and sometimes insufficient aeration hampered satisfactory root growth (cf. Chapter 9). Hence, sugar content was usually lower and root and, averaged for annual nitrogen levels, sugar yields were 10 - 15% lower than on ploughed soil.

Seedbed preparation and sowing of spring barley in one pass did not pose any problems in Systems A and C. However, in System B1 the seedbed was coarser and shallower and sometimes local slaking occurred, which caused an irregular stand. In System B2 the sowing technique was not perfect and sometimes the seed was not covered very well, which hampered emergence and induced severe bird damage. Moreover, the surface was very uneven and, in wet springs, seedlings suffocated in dips, which resulted in an irregular stand. Therefore, it was fully justified to increase the seed rate by 23% on average. In untilled soil, especially in System B2, initially root and shoot growth lagged behind. Later in the growing season some compensational growth was observed (cf. Chapter 8). During the second crop rotation the nitrogen response of spring barley usually was only small; at the highest annual nitrogen level yields were similar in all systems.

Generally, the normal, intensive weed control as practiced here was effective in all systems, i.e. weed coverage was always well below the threshold value. In sugar beet, however, additional hoeing and hand weeding was needed in all systems. With time, no trend in the weed population was detected. The frequency of perennial weeds in Systems A and C was similar but annual weeds were somewhat less frequent in System C than in System A. In Systems B1 and B2, due to the often more open and irregular stand of the crops, more annual and perennial weeds occurred, and/or weed development was more abundant than in Systems A and C. Sometimes this required additional sprayings and hand weeding. However, in seed grass (System B2), competition by the crop was so strong that in the year the grass was harvested weed control was not necessary; also, in this crop fewer species were found than in the other crops.

Chemical control of diseases and pests was effective in all systems and differences between systems were not observed. However, small animals and birds felt at home on the mulch-covered soil of System B2 and they sometimes caused damage. Also for this reason in System B2 seed rates of cereals were increased by 20 - 30% as compared with System C.

For non-tilled soil mulch is important as it protects the soil against the beating action of rain. However, when more than 4 t ha^{-1} of dry matter remained, especially when the distribution was irregular, mulch hampered the emergence of field beans and sugar beet. Burning the heavy seed grass stubble caused local slaking, sometimes to the extent that the crop failed. In spring, sowing grass under winter wheat was difficult because the non-tilled soil often was too hard for a conventional seeder. However, later on the scanty grass could profit from the less abundant growth of the cover crop, to the effect that, finally, a satisfactory crop of green manure grass was obtained.

The economic analysis of the second crop rotation showed that the effect of combining field operations on task time in System A (17.7 h ha^{-1}) was more or less outweighed in System C (17.9 h ha^{-1}) by the effect of the larger working width at ploughing for potatoes and at fixed-tine cultivation for cereals. In System B1, full-width rotary cultivation for seedbed preparation for potatoes and sugar beet took so much time that, averaged for the four crops, task time was 6% higher (18.9h ha^{-1}) than in Systems A and C.

In System B1 costs for herbicides to kill weeds and green manure grass were 33% higher, whereas yields of sugar beet and saleable yield of potatoes were, on average, 10 - 15% lower than in Systems A and C. In Systems A and C, differences in profit, averaged for the crop rotation, were only small. However, on a 60 ha farm, due to higher contractor's costs, profit in System A would be slightly lower than in System C; in System B1 profit would be clearly negative.

After termination of the experiment, ploughing the entire former experimental field to a depth of 28 cm gave a final opportunity to assess differences in soil structure obtained by applying the three tillage systems during 8 years. The potatoes that were grown in the first year after termination of the experiment served to test after-effects of the three tillage systems on crop growth.

The effect of ploughing was similar for Systems A and C, as it was for Systems B1 and B2. This confirms that differences in soil structure between Systems A and C on the one hand and Systems B1 and B2, on the other, were only small. The greater compactness of the soil in Systems B1 and B2 was reflected in a 20% higher specific ploughing resistance. The relationship between total pore space and specific ploughing resistance showed much more variability for untilled than for tilled soil. This confirms that untilled soil has many more natural cracks and fissures than tilled soil. This may also explain that the degree of soil crumbling in untilled soil generally was about the same as in tilled soil. The exception was sugar beet where, on untilled soil, the degree of soil crumbling was similar to potatoes, winter wheat and spring barley, but on tilled soil, probably due to severe compaction during harvesting sugar beet late and under wet conditions, soil crumbling was only slight and, thus, soil surface roughness was higher and slaking during winter less than after the other crops. Another consequence of the dense state of the untilled soil was that upheaval at ploughing was about 40% larger in Systems B1 and B2 than in Systems A and C. Thus, the originally much denser untilled soil became even slightly looser than the always tilled soil.

In spring 1980 when the soil was still bare, former System B plots had on average a 0.7°C higher surface temperature than System A, which accords with the lower moisture content in the surface layer (0 – 5 cm) of System B. In Systems B1 and B2, the seedbed for potatoes was thicker, it contained less clods >20 mm and was, on average, much finer and moisture content was less than in Systems A and C. Initially, directly below the seedbed, mean pore space and moisture content were slightly higher than in Systems A and C. In System B2, after all previous crops, moisture content at 10 – 20 cm below the ridge was 2% higher than in the other systems. This accords with the fact that in System B2 the original surface layer was much higher in organic matter than in the other systems. In June 1980, a final core sampling showed that all differences in pore space, moisture and air content between former tillage systems had disappeared.

In 1980, B1-plots after potatoes and sugar beet, had more perennial weeds. On the former winter wheat and spring barley plots, potato foliage developed slightly better and it died slightly later in System B2 than in the other systems. Probably, this was caused by a greater nitrogen supply by nitrification on former B2-plots, due to tillage for the first time after eight years of no-tillage.

16 General conclusions

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1. Loose-soil husbandry (System A), based on ploughing each year to 25 cm, was not a favourite, when compared with rational tillage (System C). Due to the large ploughing depth, no problems occured with respect to turning under trash, green manure grass and weeds. Consequently, only normal use of herbicides had to be made. However, combination of seedbed preparation and sowing or planting in spring was not effective in sparing soil structure because often relatively large tractors (up to 80 kW) were required and soil moisture content was usually higher than desirable, which increased both the degree of compaction and the area compacted. To maintain the loose soil over a substantial part of the field, wider working widths would be desirable. A possible solution could be to increase the track gauge of the tractor wheels considerably beyond the present 1.50 m, and to establish (permanent) traffic lanes. However, for application in practice this system needs further development.

2. Rational tillage (System C), which tried to meet the minimum requirements of the crops, gave slightly better results than System A, in crop yields as well as in financial terms. The generally smaller tillage depths and non inverting tillage for cereals were attended by larger working widths, but the covering of thrash, green manure grass, volunteer plants and weeds was not always satisfactory. Hence, the system was slightly more dependent on herbicides than the loose-soil husbandry system.

3. No-tillage in a rotation with root crops (System B1) proved to be practicable only if, as was practiced in the second crop rotation, for all crops a proper seedbed was prepared. However, in autumn, after potato harvest, seedbed preparation for winter wheat always resulted in much too fine a seedbed, which sometimes severely slaked during winter and early spring. Since in spring the untilled soil remained wet much longer than tilled soil, seedbed preparation for potatoes, sugar beet and spring barley was difficult and often it had to be delayed. Moreover, it required much more energy and usually it resulted in a coarser tilth than on tilled soil. The system had to rely heavily on herbicides for killing green manure grass, volunteer cereal plants and weeds. However, volunteer potato plants were never a problem.

4. No-tillage in a rotation with non-root crops only (System B2) was difficult to perform because the drilling technique used was not good enough for the circumstances. Soil moisture conditions were often not favourable, causing either smearing of the slits or insufficient penetration of the coulters of the proto-type triple disc drill and, thus, unsatisfactory coverage of the seed, sometimes inducing severe bird damage. Moreover, natural dips and ruts due to field traffic could not be removed and, therefore, during wet

periods, parts of the field were often turned into small ponds in wich sometimes seedlings suffocated. The system proved to be extremely dependent on herbicides for killing green manure grass and weeds, especially perennial species.

5. Although after conclusion of the first crop rotation (1972 - 1975) differences in depth of primary tillage between System A and C were increased, during the second crop rotation (1976 - 1979) differences in soil structure between these systems again were only small. Probably, this was due mainly to the small differences in traffic intensity between these systems and to better soil conditions during harvest of root crops and subsequent primary tillage operations during the second than during the first crop rotation.

6. Non-tilled soil (Systems B1 and B2) already in the very first growing season (1972) had a clearly lower pore space than tilled soil. In subsequent years pore space still further decreased due to compactive effects of harvest operations but, after harvest in the wet autumn of 1974, it remained rather stable at a low (22 - 27 cm layer) or very low level (12 - 17 cm layer). However, in these layers, the slightly better gas diffusion and air permeability at the same low air content points to a somewhat better continuity of the system of big(ger) pores than on tilled soil. In the 2 - 7 cm layer there was a gradual increase in pore space, due to seedbed preparation for all crops (System B1) and/or organic matter accumulation (System B2).

7. In the arable layer the number of roots did not vary much between Systems A and C but, on average, significantly fewer roots were found in System B1. Thus, the looser structure of the tilled layer clearly promoted root-growth. The ploughpan, which was very compact in all systems, and the subsoil, which was only slightly less compact, were not very favourable for root development. For potatoes, in all systems, the lower limit of the effective rooting zone, i.e. the part of the profile that contained 90% of the roots, even coincided with the upper limit of the ploughpan (about 30 cm). Effective rooting depth for winter wheat was about 90 cm, for spring barley 80 cm and for sugar beet 50 cm.

8. In the beginning of the experiment, in untilled soil, less nitrogen was available but, after one four-year crop rotation including root crops (System B1), nitrogen availability was equal to that in tilled soil. In a crop rotation without root crops (System B2), this situation was reached at least two years later.

9. Crop yields and crop response to fresh nitrogen applications were very variable between years, due to differences in weather conditions and mineral nitrogen reserves in the soil profile (0 - 100 cm). Mineral nitrogen reserves in January were dependent on the previous crop and the weather conditions during the previous autumn and winter. Even in a relatively dry winter a considerable amount of nitrogen was leached from the topsoil. In a relatively wet winter, losses by leaching and denitrification clearly increased. During the second crop rotation, after winter wheat, spring barley and sugar beet, similar amounts of mineral nitrogen were found, but after potatoes, probably due to superficial rooting, about twice as much was found. Significant effects of perennial nitrogen levels of 20% plus or minus the normal rate on the amount of N_{min}, as determined in January, were not found.

10. In untilled soil, especially in the surface layer, phosphate was more readily available to the plant than in tilled soil. Total amounts in the topsoil were only slightly larger in untilled than in tilled soil.

11. With respect to crop yield of potatoes, winter wheat, sugar beet and spring barley, loose-soil husbandry was not superior to rational tillage. Moreover, when in System A combined seedbed preparation and planting or sowing took place under unfavourable, wet soil conditions for the rather heavy machinary used, potato ridges were too small and of poor quality and the seedbed for sugar beet was to coarse and/or seed coulters clogged, resulting in an irregular stand. Under these conditions yields tended to be lower than in System C by about 5%.

12. In System B1, mainly due to the unfavourable soil structure, the effects of which are elucidated in detail in Chapters 8 and 9, yields of potatoes and sugar beet were usually 10 – 15% lower than in System C. Thus, especially for root crops, extremely reduced tillage (seedbed preparation only) is unacceptable. Provided normal nitrogen rates were increased by 15 – 20%, with winter wheat, except for failures due to severe slaking, and with spring barley, which never failed, yields were on average only 4% less than in Systems A and C.

13. In System B2, where all tillage was omitted, seed grass and field beans gave reasonable yields. For cereals, normal nitrogen rates and seed rates had to be increased by 15 – 20% and about 25%, respectively. Even so, when winter wheat did not fail, which it easily did because of smeared slits and the uneven, often ponded soil surface (dips and ruts), it yielded 0 – 5% less than in System B1. Spring barley, when sown on time, yielded only 2% less than in System B1. However, generally, due to many failures, even for cereals in a non-root crop rotation, 'pure' zero-tillage is not attractive under Dutch conditions.

14. During the first crop rotation there were no cumulative effects of different perennial nitrogen levels on crop yields. Large variations in fresh nitrogen applications at perennial nitrogen levels during the second crop rotation prevented a clear demonstration of possible cumulative effects during this period.

15. Mulch from plant remains protected the soil against slaking, but it favoured harmful animals and birds and it hampered the drying up of the soil in spring. When a thick layer of mulch is present, seedbed preparation and sowing in spring may be delayed for several weeks. Even when the distribution of the mulch is satisfactory, for sugar beet not more than 2 t ha^{-1}, and for cereals and seed grass not more than 4 t ha^{-1} of dry matter should be left on the surface. Therefore, seed grass straw should always be removed or burnt, and the regrowth of the stubble killed off with glyphosate and subsequently burnt.

16. On a sunny day prior to spring cultivations, thermal imagery showed that plots in System B1 (after cereals), in System B2 (after all crops) and in System C (after spring barley) had higher surface temperatures than bare plots. This was due to differences in soil coverage with mulch and not to differences in moisture content.

17. 'Pure' zero-tillage (System B2) favoured the earthworm population and, consequently, considerably more biopores > 1.5 mm, but also < 1.5 mm, were found than on tilled soil. This may have contributed to the fact that, at a comparable small air content, the non-tilled soil had a higher gas diffusion than tilled soil.

18. The economical evaluation of the tillage systems in the second crop rotation, based on the actual costs, and on the yields obtained at optimal nitrogen levels, showed that, due to higher costs of mechanization and, in some years, lower yields, profits in System A were slightly less than in System C. For System B1, due to 10 – 15% lower yields of root crops and substantial higher costs of herbicides and, for potatoes, sugar beet and spring barley, higher costs of seedbed preparation, profits would be about Dfl. 700 per ha (US$250, per ha) lower and thus clearly negative.

19. After termination of the experiment, upon ploughing the entire former experimental field to about 28 cm depth, the much denser and compacter soil in Systems B1 and B2 manifested itself in a 20% higher specific ploughing resistance, a much stronger degree of crumbling after sugar beet, and a 40% larger upheaval than in Systems A and C. In the next spring, soil surface temperature in System B was 0.7°C higher than in System A, because of a lower moisture content. In Systems A and C after sugar beet, and in System B1 after potatoes, soil surface roughness was high and reflectance was low. The separate plots of the former experimental field were still clearly visible on both false-colour and thermal images.

20. In the year after termination of the experiment (1980), on the former System B1 and B2 plots, the seedbed for potatoes (the test crop on the entire former experimental field) was much thicker and finer and, below the seedbed, mean pore space and moisture content were initially slightly higher than in Systems A and C. On former B2 plots, at 10 – 20 cm below the ridges, due to turning under a surface layer that was rich in organic matter, moisture content was initially about 2% (w/w) higher than in the other systems and, due to a stronger nitrogen mineralization, foliage of potatoes developed better and died later than in the other systems. On the former System B1 potato and sugar beet plots, more perennial weeds developed than in the other systems. In June 1980, pore space, moisture and air content to 20 cm depth below the potato ridges were similar for all former tillage systems. Thus, even though performed under wet soil conditions, by ploughing to 28 cm depth the effect of eight years of no-tillage was fully removed.

Summary

During 1976 – 1979 the second four-year period of a soil tillage experiment was conducted which had been started in the autumn of 1971 on a marine loam soil (22% clay) at Westmaas Experimental Husbandry Farm (Westmaas Research Group on New Tillage Systems, 1980). Three tillage systems were compared in a four-year crop rotation: potatoes – winter wheat + undersown grass – sugar beet – spring barley + undersown grass.

Loose-soil husbandry (System A) was devised to produce and maintain a looser soil structure than presently found in arable fields. During 1976 – 1979, primary tillage was autumn ploughing to 25 cm for all crops, for winter wheat combined with sowing in one pass. In spring, to reduce traffic intensity and therefore compaction, nitrogen application, secondary tillage and sowing or planting were also combined into one pass.

In no-tillage (System B), primary tillage was omitted. During 1976 – 1979, either only a seedbed was prepared for all crops (System B1) or, in an alternative four-year crop rotation with non-root crops only: seed grass – winter wheat + undersown grass – field beans – spring barley + undersown seed grass, direct drilling was performed (System B2).

Rational tillage (System C) tried to meet supposed reasonable minimum requirements of the crops with respect to soil structure and weed control. During 1976 – 1979, primary tillage (in autumn) consisted of ploughing to 25 cm depth (for sugar beet) or to 15 cm depth (for potatoes), or fixed-tine cultivation to 15 cm depth (for cereals). In spring, secondary tillage was performed in the same way as in System A and, for spring barley, was combined with sowing in one pass. However, for potatoes and sugar beet, seedbed preparation and planting or sowing were done in separate passes.

After harvest, the grass, sown in spring under cereals, was fertilized with 50 kg ha^{-1} N to develop into a satisfactory green manure. Tops and leaves of sugar beet were left on the field and cereal straw was chopped and spread, except for winter wheat straw in System B1, which was baled and removed to safeguard sugar beet emergence. In Systems A and C, these organic materials were incorporated into the soil but in Systems B1 and B2 they were left on the surface to serve as a mulch, if appropriate (green manure grass, seed grass stubble) after killing off with herbicides.

Tillage-induced changes in nitrogen availability were studied by five equidistant 'annual' nitrogen levels, ranging from 0 to 200% of the amounts applied in practice. These 'annual' nitrogen levels were laid out each year in all four main crops but, to avoid possible cumulative effects, each year on only one of the three repetitions of the experimental field. Thus, 'annual' nitrogen levels were not replicated. In contrast, to induce cumulative effects, three 'perennial' nitrogen levels, equal to 80, 100 and 120% of the amounts applied in practice, were laid out each year on the same places on all three repetitions of the experimental field.

In all three systems the normal, intensive chemical control of weeds, diseases and pests was applied. In sugar beet, in all systems, chemical weed control was supplemented by hoeing and hand weeding.

In loose-soil husbandry and rational tillage, soil structure was clearly better than during the 1972 – 1975 period, because of better weather and soil conditions at tillage time. However, due to the counteracting effect of field traffic, differences between System A and C remained only small. In these systems, mean pore space was about 46% (v/v) and air content at pF 2.0 about 12.5% (v/v). In Systems B1 and B2, due to seedbed preparation for all crops (System B1) and organic matter accumulation (especially System B2), pore space in the 2 – 7 cm layer (about 43%, v/v) was clearly higher than in deeper layers (about 40%, v/v), but air content at pF 2.0 was still low (about 8%, v/v).

In tilled soil, the gas diffusion coefficient was about 4 times as high as in untilled soil. However, at small air contents (<10%, v/v), it was slightly higher on untilled than on tilled soil. This indicates that pore continuity of the big(ger) pores was better on untilled than on tilled soil. In untilled soil, aeration was insufficient only under wet soil conditions (about pF 1.5).

Penetration resistance on untilled soil (about 2.5 MPa at pF 2.0) was 2 – 3 times larger than on tilled soil. In all systems the ploughpan was very compact (pore space about 40%, v/v; penetration resistance >2.0 MPa), especially restricting root growth of potatoes. However, roots of cereals and sugar beet were able to penetrate the ploughpan. In the subsoil, pore space as clearly higher (about 45%, v/v) but penetration resistance was only slightly lower as in the ploughpan. In general, the subsoil was not very favourable for root growth. In Systems A and C the total number of roots was similar but, on average, significantly fewer roots developed in System B1.

In January, in Systems A and C, the mineral nitrogen reserve in the soil profile (0 – 100 cm depth) was similar. In System B1, N_{min} increased from 60% in 1972 to 100% in 1976 of N_{min} in Systems A and C; during 1976 – 1979 it remained at this level. In System B2 it took two years more to reach this situation.

During 1976 – 1979, perennial nitrogen levels were not constant because each year they were adjusted to the mineral nitrogen reserve in the soil profile in January. From comparison with the yield response curves obtained with annual nitrogen levels it appeared that perennial nitrogen levels usually were sub-optimal. At comparable fresh nitrogen applications, yield results of both kinds of nitrogen levels were similar. Thus, perennial nitrogen levels did not show clear cumulative effects on crop yield.

In accordance with the similar soil structure, in Systems A and C crop yields of the four main crops generally were similar. In System B1, gross yield of potatoes did not differ much but, due to a much higher proportion of cullings, saleable yield was 10 – 15% lower than in Systems A and C. Due to the large penetration resistance and sometimes insufficient aeration, root and sugar yields of sugar beet were 10 – 15% lower than on ploughed soil. However, provided plant density was high enough and normal nitrogen rates were increased by 10 – 20%, yields of winter wheat and spring barley were about the same as in Systems A and C. In System B2, the sowing technique was not perfect and during wet periods the uneven surface often was partly ponded. Therefore, although normal seed rates of cereals were increased, winter wheat failed in 1976 and nearly failed in 1978. When it did not fail it yielded 0 – 5% less than in System B1. Spring barley never failed but, initially, root and shoot growth lagged behind and yield was slightly lower than in System B1. Field beans and seed grass gave reasonable yields. Especially seed grass, which covers the field for almost 14 months, seems suitable for 'pure' no-tillage.

In all systems the intensive weed control kept the weed coverage well below the threshold value. In Systems A and C the frequency of perennial weeds was similar but annual weeds were more frequent in System A than in System C. In Systems B1 and B2, due to the omission of primary tillage and to the more open and irregular stand of the crops, development of both annual and perennial weeds was more abundant than in Systems A and C, sometimes requiring additional sprayings and hand weeding.

When, in spring, plant remains left on non-tilled soil as a mulch, still amounted to 4 t ha^{-1} or more of dry matter, especially when the distribution was irregular, the emergence of field beans and sugar beet was hampered. In contrast, when, after burning a heavy seed grass stubble, locally too little mulch remained, slaking occurred, inducing suffocating of winter wheat seedlings. In all systems, sowing green manure grass seed together with spring barley seed was successful. However, on non-tilled soil, due to the high penetration resistance of dry soil in spring, sowing of green manure grass seed under winter wheat with a conventional seeder was difficult and only after winter wheat harvest the scanty grass could develop into a satisfactory crop.

An economical analysis showed that, averaged for the second four-year crop rotation (1976 - 1979), profits in Systems A and C were similar and positive. However, due to substantially higher costs of herbicides and clearly lower yields of root crops, in System B1 the profit was clearly negative.

After termination of the experiment, at ploughing the entire former experimental field to a depth of 28 cm, the larger compactness in former Systems B1 and B2 caused a 20% higher specific ploughing resistance and, due to a high degree of soil crumbling, a 40% larger upheaval than in former Systems A and C. In June 1980, all differences in soil structure between former tillage systems had disappeared. However, in former System B2, probably due to increased nitrogen mineralization, foliage of the test crop potatoes developed slightly better and it died slightly later than in the other former systems. Thus, although ploughing was performed under wet soil conditions, it successfully removed the effects on soil structure of eight years no-tillage.